Lawrence Livermore National Laboratory

Science & Technology Review

September 2014

Sharper Focus for Adaptive Optics

Also in this issue:

Mapping Computer Networks

Improved Treatment for Aneurysms

Engineered Foams for Stockpile Stewardship

About the Cover

Livermore researchers are part of an international collaboration that developed the Gemini Planet Imager (GPI), which is deployed on the Gemini South telescope (shown on the cover). The advanced adaptive optics system in GPI improves image resolution by removing distortions that occur when light passes through a turbulent medium such as Earth's atmosphere. As described in the article beginning on p. 4, GPI achieves this high resolution by measuring the wavefront of light observed through Gemini South at nearly 2,000 locations and at 1,000 times per second. Livermore researchers are also developing an adaptive optics system to correct x-ray beams for a new generation of high-energy research facilities. The back cover shows a twilight view from the telescope. (Gemini photographs by Marshall Perrin, Space Telescope Science Institute. Starlight composite © benjaminjk – Fotolia.com.)

Cover design: Tom Reason

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

The Laboratory is operated by Lawrence Livermore National Security, LLC (LLNS), for the Department of Energy's National Nuclear Security Administration. LLNS is a partnership involving Bechtel National, University of California, Babcock & Wilcox, Washington Division of URS Corporation, and Battelle in affiliation with Texas A&M University. More information about LLNS is available online at www.llnsllc.com.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the Web at str.llnl.gov.

National Nuclear Security Administration

Prepared by LLNL under contract DE-AC52-07NA27344

Science & Technology Review

September 2014

Lawrence Livermore National Laboratory

Contents

S&TR Staff

Scientific Editor
Gregory C. Burton

Managing Editor
Ray Marazzi

Publication Editor
Carolin Middleton

Writers
Rose Hansen, Arnie Heller, Caryn Meissner, M. H. Rubin, and Katie Walter

Art Director
Tom Reason

Proofreader
Pamela MacGregor

Print Coordinator
Charlie M. Arteago, Jr.

S&TR, a Director's Office publication, is produced by the Technical Information Department under the direction of the Office of Planning and Special Studies.

S&TR is available on the Web at str.llnl.gov

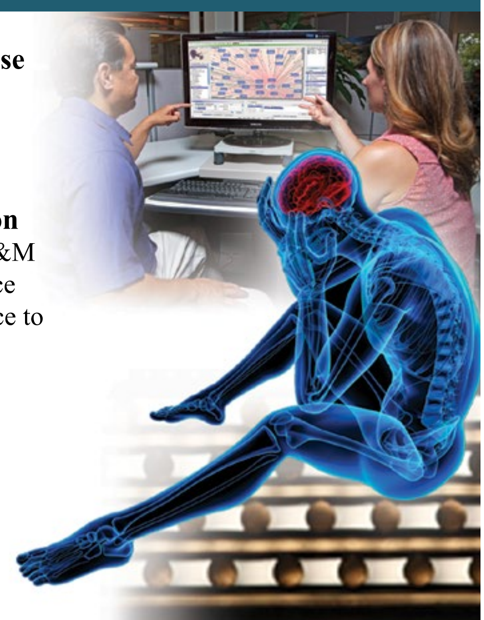
Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-14-9
Distribution Category UC-99
September 2014

Feature

Research Highlights



Departments

Laboratory Garners Four R&D 100 Awards

Four technologies developed by Livermore researchers and their collaborators received R&D 100 awards from *R&D Magazine* in its annual competition to honor top scientific and engineering technologies with commercial potential. This year's award winners are as follows:

• A miniaturized, field-portable thin-layer chromatography (TLC) kit called microTLC™ detects and identifies explosives compounds, illicit drugs, and other hazardous materials.

• The superconducting tunnel junction x-ray spectrometer offers an energy resolution 10 times greater than that from x-ray spectrometers based on silicon or germanium semiconductors.

• The extreme-power, ultralow-loss, dispersive element (EXUDE) spectrally combines beams from many small lasers into a single high-power beam with high efficiency and beam quality.

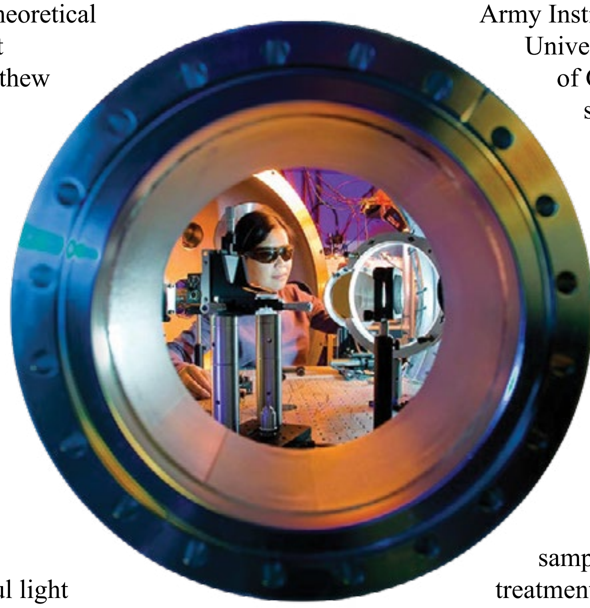
• Convergent polishing is a fast, inexpensive process for finishing the flat and spherical glass optics used in high-energy lasers, imaging systems, and lithography and for manufacturing optical components.

Since 1978, the Laboratory has captured 152 R&D 100 awards. The October/November issue of *S&TR* will highlight these award-winning inventions and the researchers who developed them.

Contact: Richard A. Rankin (925) 423-9353 (rankin8@llnl.gov).

Absorption Limits Defined for Petawatt Lasers

Scientists from Lawrence Livermore and Rice University have, for the first time, defined a set of theoretical boundaries for the absorption of petawatt (10^{15}-watt) laser light. According to Matthew Levy, a Lawrence Scholar from Rice University, the team's analysis reveals the fundamental limits of how these powerful light sources interact with dense matter and convert laser energy to particle energy. "Because the interaction is so nonlinear, a key outstanding problem has been predicting the amount of light absorbed," says Levy, who works in the Laboratory's Physical and Life Sciences Directorate. Defining these boundaries will help researchers better understand the physics involved in experiments on solid targets.



"Petawatt lasers are the most powerful light sources ever created," says Levy, who led the research team. Irradiating solids with a petawatt laser (above) creates temperatures greater than 10 million degrees and pressures above 10^{14} pascals (1 billion atmospheres). These high-energy-density conditions are driven by violent absorption processes, which can accelerate electrons from rest to 99.9 percent of the speed of light over just a few micrometers. Suitably harnessed, these conditions can be applied to advanced technologies such as compact radiation sources, laser fusion, laboratory-scale astrophysics research, and ultrafast imaging systems.

In addition to Levy, the research team included Livermore physicists Scott Wilks, Max Tabak, and Steve Libby as well as Matthew Baring from Rice University. The team's advanced theoretical model appeared in the June 18, 2014, edition of *Nature Communications*.

Contact: Matthew Levy (925) 422-4524 (levy11@llnl.gov).

Improved Pathogen Detection in Combat Wounds

A collaboration led by Laboratory researchers has used a new technology that detects more biological pathogens in wounds than traditional methods. The team found that the Lawrence Livermore Microbial Detection Array (LLMDA) identified microorganisms in at least one-third of U.S. soldiers whose wounds had been declared free of microbes. The study results appeared in the July 2014 issue of *Journal of Clinical Microbiology*.

Established pathogen-detection systems require time to cultivate microbes before determining whether infectious organisms are present. LLMDA uses 180,000 probes to determine within 24 hours whether any of the 3,855 sequenced bacteria or 3,856 sequenced viruses contaminate a wound. The collaboration—which included investigators from Naval Medical Research Center, Walter Reed Army Institute of Research, Uniformed Services University of the Health Sciences, and University of California at Davis—analyzed 124 wound samples from 44 U.S. soldiers injured in Iraq and Afghanistan. LLMDA was sensitive enough to detect bacteria such as *Pseudomonas* species and *Acinetobacter baumannii* in many of the wounds that had failed to heal correctly. According to Livermore scientist Nicholas Be, who led the research, certain pathogens that are important to wound healing are difficult to grow in a laboratory and thus may not be identified by the standard culture-based detection methods.

Be notes that, although the study analyzed samples from soldiers, the results could benefit treatments for burn trauma and diabetic ulcers. Since wound infections delay rehabilitation and increase hospital stays, LLMDA's success in identifying bacterial pathogens would help medical professionals personalize treatment and accelerate patient recovery.

Contact: Nicholas Be (925) 423-1612 (be1@llnl.gov).

Commentary by Monya Lane

Extreme Engineering Key to Adaptive Optics Advances

THROUGHOUT Lawrence Livermore's 62-year history, one of its enduring competitive strengths has been its ability to rapidly mobilize multidisciplinary teams to respond to an exceptionally wide variety of customer needs. This concept is particularly evident within the 1,500-member Engineering Directorate. Livermore engineers—computational, electrical, mechanical, chemical, and optical—play leading roles in many Laboratory projects, working alongside physicists, computer scientists, chemists, geologists, and other researchers.

An outstanding example of teamwork was the nearly decade-long effort to design and build the Gemini Planet Imager (GPI), the first astronomical instrument for directly imaging and analyzing planets outside our solar system. Attached to the Gemini South telescope in Chile, GPI uses a technology called adaptive optics to compensate in real time for the twinkling of starlight caused by Earth's turbulent atmosphere and thereby produce much clearer images of stars and planets.

GPI's adaptive optics system serves as a showcase for Livermore engineers' prowess in pushing the limits of technology, as described in the article beginning on p. 4. The GPI system produces the clearest images of extrasolar planets (exoplanets) ever recorded and performs about 70 times more quickly than existing instruments in detecting exoplanets many light-years away. The instrument, currently in its final shakedown phase, is operating superbly. Over the next three years, Gemini imaging results are expected to strengthen scientific understanding of how planetary systems form and evolve, how planets' orbits change, and what comprises their atmospheres.

To meet GPI's stringent operational requirements, a Livermore team of optical, computational, and electrical engineers, working closely with astrophysicists and astronomers, developed several technologies that exploit the power of adaptive optics to search for exoplanets. The engineers devised a remarkably agile system that measures the light passing through the Gemini South telescope 1,000 times per second at nearly 2,000 control points in the telescope's 8-meter aperture. Every thousandth of a second, the system corrects for distortions by adjusting the shapes of two deformable mirrors. The one designed for fine focusing measures only 2 centimeters on a side, yet it employs 4,096 tiny microelectromechanical actuators. Another Livermore advance, a self-optimizing computer system, controls the actuators with computationally efficient algorithms that are continually determining the ideal position for each actuator.

Building on the expertise gained from developing GPI, the Laboratory is bringing adaptive optics technology for visible light to the world of x-ray optics. If adaptive optics systems could correct common distortions in x-ray beams, Department of Energy high-energy research centers could reach their theoretical limits and achieve improved resolution to advance research in physics, chemistry, and biology. Working with industry, we have designed and built an x-ray deformable mirror that will be a key component of an adaptive x-ray optics system. We are testing this mirror along with new x-ray beam diagnostics at Lawrence Berkeley National Laboratory's Advanced Light Source.

Our successful engineering accomplishments in adaptive optics, as with so many other research projects, serve as a compelling inducement to attract talented scientists and engineers to Livermore. For example, under our tutelage, two graduate students from the University of California are working on advanced adaptive optics algorithms.

In addition to the feature article, this issue of *Science & Technology Review* highlights three important initiatives in which engineers have substantial roles. The first article, which begins on p. 13, describes how computational engineers helped develop a new software tool for enhanced cybersecurity. The second, beginning on p. 16, details how chemical, materials, and computational engineers have combined advanced materials development and computational analysis into a new approach for treating brain aneurysms. Finally, beginning on p. 20, we report on improved cushions to protect nuclear weapons components, thanks to novel additive manufacturing techniques that create new kinds of exquisitely engineered materials.

The enduring success of Livermore engineers working comfortably with researchers from a host of disciplines, institutions, and industrial partners illustrates the creative power of engineering innovation. With these most recent advances in adaptive optics, we have again demonstrated how engineering enables program success and ensures the Laboratory's continuing vitality.

In November 2014, an international team of scientists begins a three-year campaign using GPI to discover and characterize giant exoplanets. We look forward to seeing the latest results of pushing engineering to the extreme.

■ Monya Lane is associate director for Engineering.

Giant Steps for Adaptive Optics

Recent advances make possible the routine direct imaging of extrasolar planets and an innovative x-ray deformable mirror.

LAST November, high in the Chilean Andes, an international team of scientists and engineers, including Lawrence Livermore researchers, celebrated jubilantly in the early morning hours. The cause for their celebration was the appearance of a faint but unmistakable image of a planet 63 light-years from Earth circling a nearby star called Beta Pictoris. The clear image was viewable from a ground-based telescope thanks to one of the most advanced adaptive optics systems in existence, a key element of the newly fielded Gemini Planet Imager (GPI).

GPI (pronounced gee-pie) is deployed on the 8.1-meter-diameter Gemini South telescope, situated near the summit of Cerro Pachón at an altitude of 2,715 meters. The size of a small car, GPI is mounted behind the primary mirror of the giant telescope. Although the imager is still in its shakedown phase, it is producing the fastest and clearest images of extrasolar planets (exoplanets) ever recorded. GPI is perhaps the most impressive scientific example of Lawrence Livermore's decades-long preeminence in adaptive optics. This technology uses an observing instrument's optical components to remove distortions that are induced by the light passing through a turbulent medium, such as Earth's atmosphere, or by mechanical vibration.

More than two decades ago, Livermore scientists were among the first to show how adaptive optics can be used in astronomy to eliminate the effects of atmospheric turbulence, which cause the twinkle we see in stars when viewing them from Earth. Those effects also create blurring in images recorded

by ground-based telescopes. Laboratory researchers have since applied adaptive optics to other fields, including lasers and medicine. For example, adaptive optics helped produce extremely high-resolution images of the retina with an instrument that won an R&D 100 Award in 2010. (See *S&TR*, October/November 2010, pp. 14–15.) Livermore teams are now working on an adaptive optics system to transport x-ray beams in a new generation of high-energy research facilities. In addition, outreach efforts by the Laboratory are strengthening educational opportunities in this field at U.S. colleges and universities.

Designed for Exoplanet Imaging

GPI is the first astronomical instrument designed and optimized for direct exoplanet imaging and analysis. Imaging planets directly is exceedingly difficult because most planets are at least 1 to 10 million times fainter than the parent stars they orbit. One way to improve image quality is to send telescopes into orbit, which boosts research costs enormously. A much less expensive approach is to equip a ground-based telescope with adaptive optics to compensate in real time for the distortions of light caused by Earth's atmosphere.

Livermore computational engineer David Palmer, GPI project manager and leader of its adaptive optics development effort, notes

The Gemini South telescope, near the summit of Cerro Pachón in Chile, is one of two telescopes operated by the Gemini Observatory. (Photograph by Marshall Perrin, Space Telescope Science Institute.)

that GPI comprises several interconnected systems and components. In addition to adaptive optics, the imager includes an interferometer, coronagraph, spectrometer, four computers, and an optomechanical structure to which everything is attached. All are packaged into an enclosure 2 cubic meters in volume and flanked on either side by "pods" that hold the accompanying electronics.

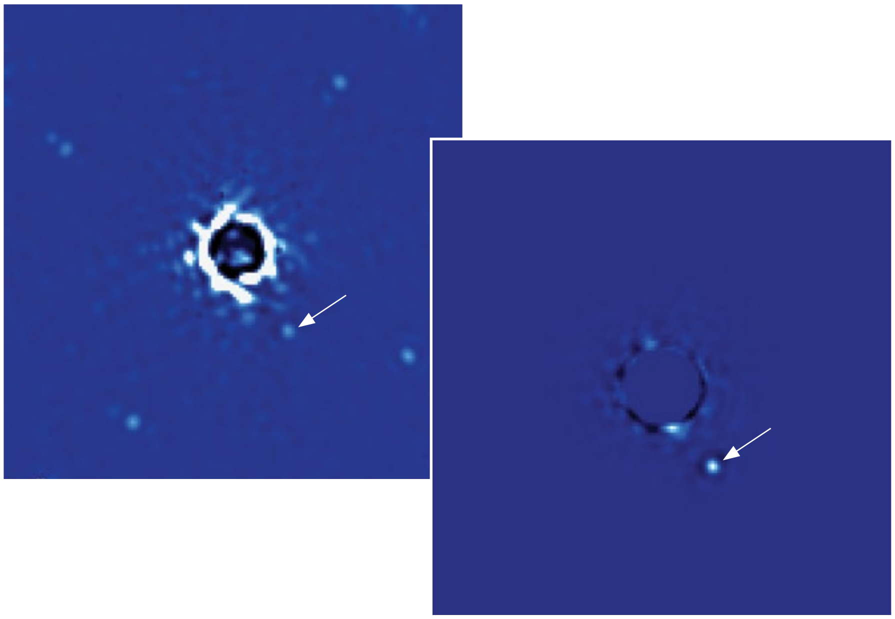
GPI hangs on the back end of Gemini South, a design that sharply constrains the imager's volume, weight, and power requirements. While in use, it constantly faces the high winds and hostile environment at high altitude. As the telescope slews to track a star, the instrument flexes, making alignment more complicated. Nevertheless, says Palmer, GPI has maintained its alignment "phenomenally well" and performed superbly. "The precision requirements worked up by the GPI design team are almost staggering," he says, "especially those for the adaptive optics system."

Laboratory electrical engineer Lisa Poyneer adds, "GPI features several new approaches that enable us to correct the atmosphere with precision never before achieved." Poyneer developed the algorithms (mathematical procedures) that control two deformable mirrors and led adaptive optics system testing in the laboratory and at the telescope.

Lawrence Livermore engineer Lisa Poyneer and Stanford University astrophysicist Bruce Macintosh (previously at Livermore) stand in front of the Gemini Planet Imager (GPI), which is installed on the Gemini South telescope in Chile. Two electronic pods (blue) on either side of the main enclosure hold GPI's electronics. (Photograph by Jeff Chilcote, University of California at Los Angeles [UCLA].)

GPI is an international project with former Livermore astrophysicist Bruce Macintosh (now a professor at Stanford University) serving as principal investigator. The Gemini South telescope is an international partnership as well, involving the U.S., Canada, Australia, Argentina, Brazil, and Chile. Macintosh says the first discussions concerning a ground-based instrument dedicated to the search for exoplanets began in 2001. "A lot of exoplanets were being discovered at that time, but the discoveries didn't tell us much about the planets themselves," he

In November 2013, members of the GPI first-light team celebrated when the system acquired its first images. The team includes: (from left to right) Pascale Hibon, Stephen Goodsell, Markus Hartung, and Fredrik Rantakyrö from Gemini Observatory; Jeffrey Chilcote, UCLA; Jennifer Dunn, National Research Council (NRC) Canada Herzberg Institute of Astrophysics; Sandrine Thomas, NASA Ames Research Center; Macintosh; David Palmer, Lawrence Livermore; Dmitry Savransky, Cornell University; Marshall Perrin, Space Telescope Science Institute; and Naru Sadakuni, Gemini Observatory. (Photograph by Jeff Chilcote, UCLA.)



(left) During its first observations, GPI captured this image within 60 seconds. It shows a planet orbiting the star Beta Pictoris, which is 63 light-years from Earth. (right) A series of 30 images was later combined to enhance the signal-to-noise ratio and remove spectral artifacts. The four spots equidistant from the star are fiducials, or reference points. (Image processing by Christian Marois, NRC Canada.)

says. “There was a clear scientific need to incorporate adaptive optics, and the technology was progressing quickly.”

After more than eight years in development, GPI components were tested and integrated at the Laboratory for Adaptive Optics at the University of California (UC) at Santa Cruz in 2012 and 2013. The imager was shipped to Chile in August 2013, with first light conducted in November.

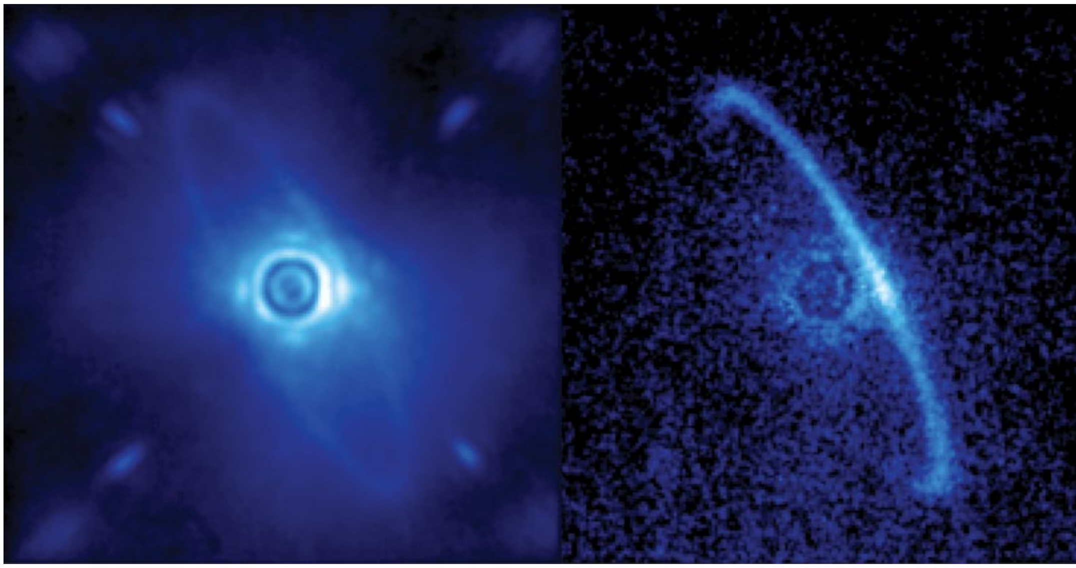
Scientists will use GPI over the next three years to discover and characterize dozens or more exoplanets circling stars located up to 230 light-years from Earth. In addition to resolving exoplanets from their parent stars, GPI uses a spectrometer to probe the composition of each exoplanet’s atmosphere. The instrument also studies disks around young stars with a technique called polarization differential imaging.

Age of Exoplanet Discovery

The discovery of exoplanets was a historic breakthrough in modern astronomy. More than 1,000 exoplanets have been identified, mainly through indirect techniques that infer a planet’s mass and orbit. Astronomers have been surprised by the diversity of planetary systems that differ from our solar system. GPI is expected to strengthen scientific understanding of how planetary systems form and evolve, how planet orbits change, and what comprises their atmospheres.

GPI masks the light emitted by a parent star to reveal the faint light of young (up to 1-billion-year-old) giant planets in orbits a few times greater than Earth’s path around the Sun. These young gas giants (the size of Jupiter and larger) are detected through their thermal radiation (about 1.0 to 2.4 micrometers wavelength in the near-infrared region).

GPI is not sensitive enough to see Earth-sized planets, which are 10,000 times fainter than giant planets. (See *S&TR*, July/August 2012, pp. 12–14.) However, it complements astronomical instruments that infer a planet’s mass and orbit by measuring the small gravitational tugs exerted on a parent star or, as with NASA’s Kepler Space Telescope, by



GPI also records data using polarization differential imaging to more clearly capture scattered light. Images of the young star HR4796A revealed a narrow ring around the star, which could be dust from asteroids or comets left behind by planet formation. The left image shows normal light scattered by Earth’s turbulent atmosphere, including both the dust ring and the residual light from the central star. The right image shows only polarized light taken with GPI. (Image processing by Marshall Perrin, Space Telescope Science Institute.)

blocking very small amounts of light emitted by the parent star as the planet passes in front of that star. “These indirect methods tell us a planet is there and a bit about its orbit and mass, but not much else,” says Macintosh. “Kepler can detect tiny planets similar to the size of Earth. With GPI, we can find much larger planets, the size of Jupiter, so the two instruments provide complementary information.”

The direct imaging of giant planets permits the use of spectroscopy to estimate their size, temperature, surface gravity, and atmospheric composition. Because different molecules absorb light at different wavelengths, scientists can correlate the light emitted from a planet to the molecules in its atmosphere.

Extreme Adaptive Optics

The heart of GPI is its highly advanced, high-contrast adaptive optics system (sometimes called extreme adaptive optics) that measures and corrects wavefront errors induced by atmospheric air motion and the inevitable tiny flaws in optics. As light passes through the Gemini South telescope, GPI measures its wavefront 1,000 times per second at nearly 2,000 locations. The system corrects the distortions within 1 millisecond by precisely changing the positions of thousands of actuators, which adjusts the shape of two mirrors. As the adaptive optics system operates, GPI typically takes about 60 consecutive, 1-minute exposures and can detect an exoplanet 70 times more rapidly than existing instruments.

To meet GPI’s stringent requirements, the Livermore team developed several technologies specifically for exoplanet science. A self-optimizing computer system controls the actuators, with computationally efficient algorithms determining the best position for each actuator with nanometer-scale precision. A spatial filter prevents aliasing (artifacts).

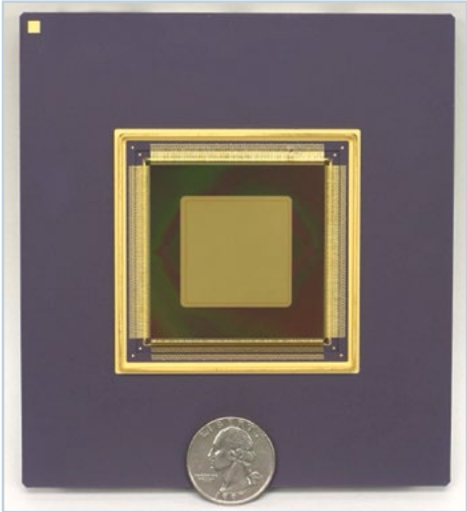
Livermore optical engineer Brian Bauman designed the innovative and compact adaptive optics for GPI. He has also worked on adaptive optics components for vision science and Livermore’s Atomic Vapor Laser Isotope System and has developed simpler systems for telescopes at the Lick Observatory and other observatories. Says Bauman, “We wanted GPI to provide much greater contrast and resolution than had been achieved in an adaptive optics system without producing artifacts that could mask a planet or be mistaken for one.”

The system corrects aberrations by adjusting the shape of two deformable mirrors. Incoming light from the telescope is relayed to the first mirror, called the woofer. Measuring about 5 centimeters across, this mirror has 69 actuators to correct atmospheric components with low spatial frequencies.

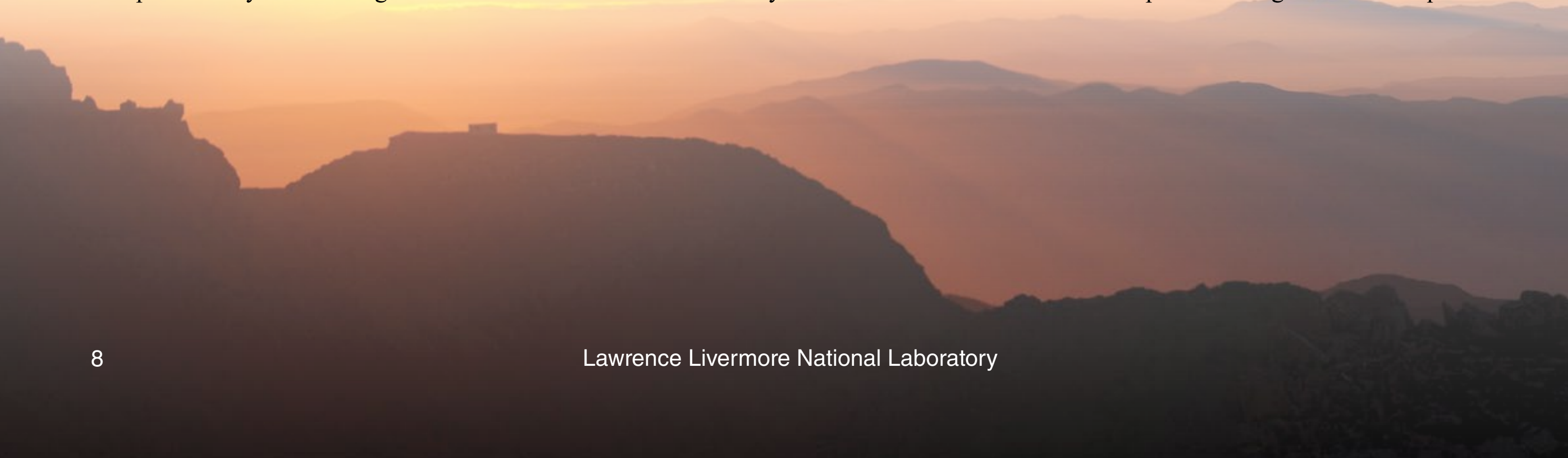
The woofer passes the corrected light to the tweeter—a 2.56-centimeter-square deformable mirror with 4,096 actuators for finer corrections. The tweeter is a microelectromechanical systems– (MEMS-) based device developed for GPI by Boston Micromachines. It is made of etched silicon, similar to the material used for microchips, rather than reflective glass. The tweeter’s actuators are spaced only 400 micrometers apart; a circular patch of 44 actuators in diameter is used to compensate for the high-spatial-frequency components of the atmosphere.

GPI has 10 times the actuator density of a general-purpose adaptive optics system. Poyneer explains that the more actuators, the more accurately the mirror surface can correct for atmospheric turbulence. “MEMS was the only technology that could give us thousands of actuators and meet our space and power requirements,” she says. “Given the number of actuators, we had to design the system to measure all aberrations at the same resolution.” This precision in controlling the mirrors is accomplished by a wavefront sensor that breaks incoming light into smaller subregions, similar to the receptors on a fly’s compound eye.

A major challenge to the increased number of actuators is that existing algorithms required far too much computation to adjust the mirrors as quickly as needed. In response, Poyneer developed a new algorithm that requires

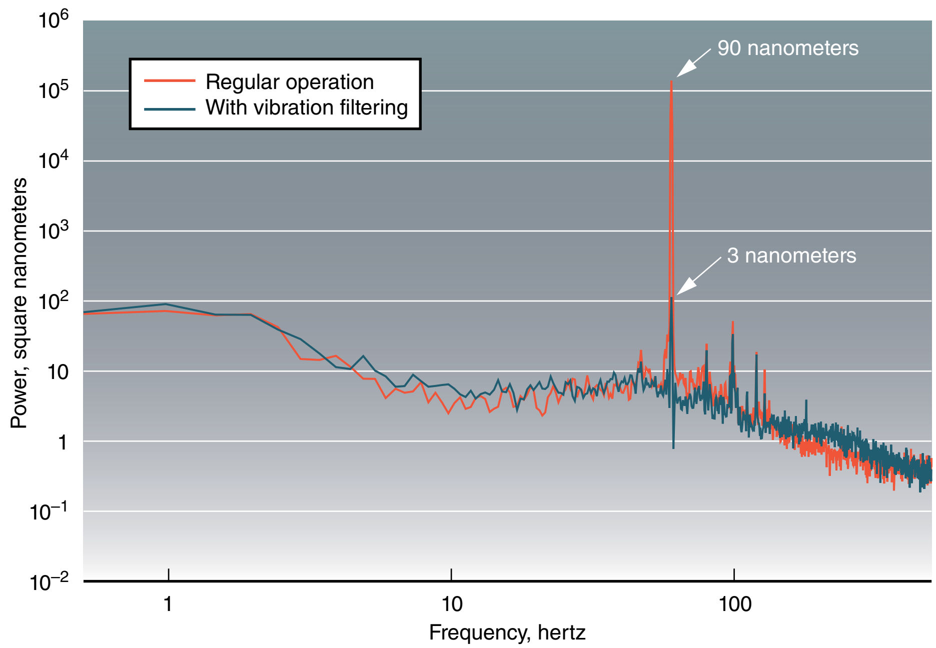


A 2.56-centimeter-square deformable mirror called a tweeter is used for fine-scale correction of the atmosphere. This microelectromechanical systems– (MEMS-) based device has 4,096 actuators and is made of etched silicon, similar to the material used for microchips. (Courtesy of Boston Micromachines.)



45 times less computation. “GPI must continually perform all of its calculations within 1 millisecond,” says Palmer, who implemented the real-time software that achieves this goal. Remarkably, the system of algorithms is self-optimized. That is, says Poyneer, “A loop monitors how the operations are going and adjusts the control system every 8 seconds. If the atmospheric turbulence gets stronger, the system control will become more aggressive to give the best performance possible.”

The mirrors forward the corrected light to a coronagraph, which blocks out much of the light from the parent star being observed, revealing the vastly fainter planets orbiting that star. Relay optics then reform the light onto a lenslet array, and a prism disperses the light into thousands of tiny spectra. The resulting pattern is transferred to a high-speed detector, and a few minutes of postprocessing removes the last remaining noise, or speckles.



The Livermore adaptive optics team has improved GPI’s performance by minimizing vibration caused by the coolers that chill the spectrometer. Vibrations inject a large focusing error into the system as the telescope optics shake. The team developed filters that reduced the focusing error by 30 times—from 90 nanometers to 3.

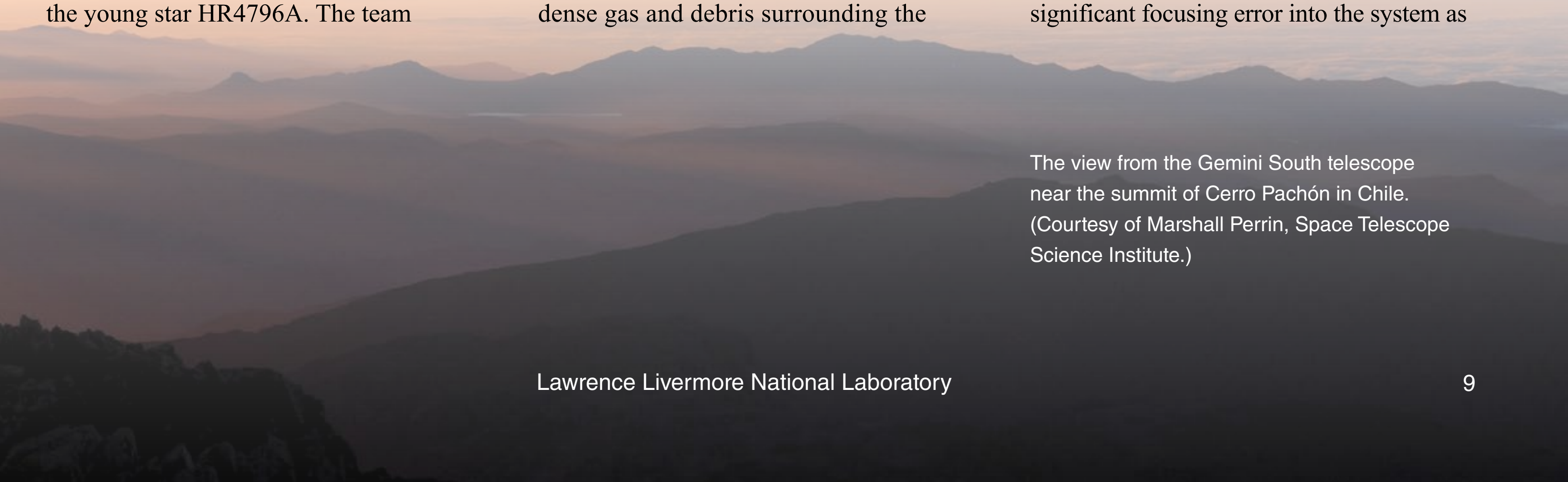
First Light November 2013

Researchers conducted the first observations with GPI in November 2013, when they trained the Gemini South telescope on two known planetary systems: the four-planet HR8799 system (codiscovered in 2008 by a Livermore-led team at the Gemini and Keck observatories) and the one-planet Beta Pictoris system. A highlight from the November observations was GPI recording the first-ever spectrum of the young planet Beta Pictoris b, which is visible as a small but distinct dot.

Using the instrument’s polarization mode, the first-light team also detected starlight scattered by tiny particles and studied a faint ring of dust orbiting the young star HR4796A. The team released the images at the January 2014 meeting of the American Astronomical Society. “The first images were a factor of 10 better than those taken with the previous generation of instruments,” says Macintosh. “We could see a planet in the raw image, which was pretty amazing. In one minute, we found planets that used to take us an hour to detect.”

Data from the first-light observations are allowing researchers to refine estimates of the orbit and size of Beta Pictoris b. To analyze the exoplanet, the Livermore team and their international collaborators looked at the two disks of dense gas and debris surrounding the parent star. They found that the planet is not aligned with the main debris disk but instead with an inner warped disk, with which it may interact. “If Beta Pictoris b is warping the disk, that helps us see how the planet-forming disk in our own solar system might have evolved long ago,” says Poyneer.

Since first light, the Livermore adaptive optics team has been working to improve GPI’s performance by minimizing vibration caused by the coolers that chill the spectrometer to a very low temperature. Vibrations decrease the stability of the parent star on the coronagraph and inject a significant focusing error into the system as



The view from the Gemini South telescope near the summit of Cerro Pachón in Chile. (Courtesy of Marshall Perrin, Space Telescope Science Institute.)

the telescope optics shake. In response, the team developed algorithms that effectively cancel the errors in a manner similar to noise-canceling headphones. The filters have reduced pointing vibrations to a mere one-thousandth of an arcsecond and decreased the focusing error by 30 times, from 90 to 3 nanometers.

In November 2014, the GPI Exoplanet Survey—an international team that includes dozens of leading exoplanet scientists—will begin an 890-hour-long campaign to discover and characterize giant exoplanets orbiting 600 young stars. These planets are located between 5 and 50 astronomical units from their parent stars, or up to 50 times the distance of Earth from the Sun (nearly 150 million kilometers). The observing time is the largest amount allocated to one group at Gemini South and represents 10 to 15 percent of the time available for the next three years. In the meantime, GPI verification and commissioning efforts continue.

Adaptive Control of X-Ray Beams

Building on the adaptive optics expertise gained with GPI, the Laboratory has launched an effort, led by Poyneer, to design, fabricate, and test x-ray deformable mirrors equipped with adaptive optics. "We took some of the best adaptive optics people in the world and put them with our experts in x-ray mirrors," says physicist Michael Pivovaroff, who initiated the program.

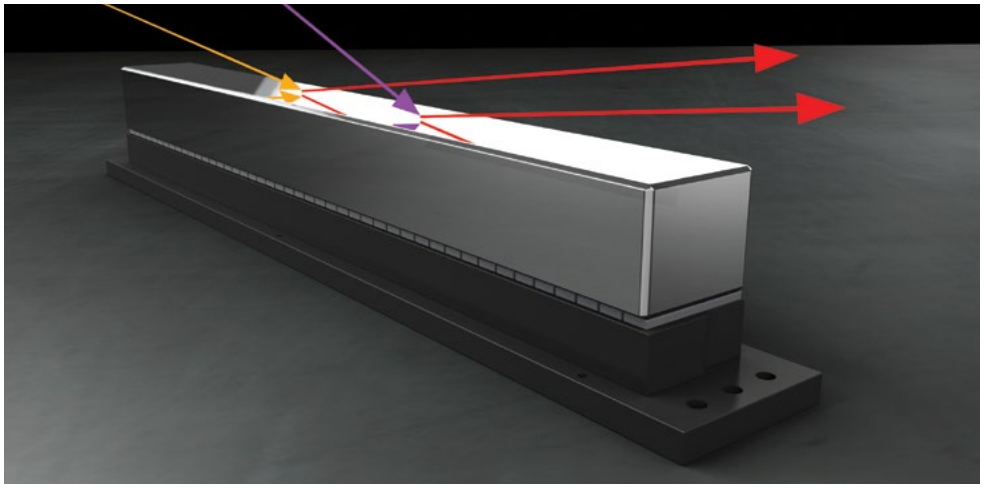
Livermore researchers previously applied their expertise in x-ray optics to design and fabricate the six advanced mirrors for the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory in Menlo Park, California. These mirrors transport the LCLS x-ray beam and control its size and direction. The brightest x-ray source in the world, LCLS can capture stop-action shots of moving molecules with a "shutter speed" measured in femtoseconds, or million-billionths of a second. With a wavelength about the size of an atom, it can image objects as small as the DNA helix. (See *S&TR*, January/February 2011, pp. 4–11.)

Despite the outstanding performance of current x-ray mirrors, further advances in their quality are required to take full advantage of the capabilities of LCLS and newer facilities, such as the Department of Energy's (DOE's) National Synchrotron Light Source II at Brookhaven National Laboratory and those under construction in Europe. "DOE is investing billions of dollars building x-ray light sources such as synchrotrons and x-ray lasers," says Pivovaroff. "Scientists working with those systems need certain spatial and spectral characteristics for their experiments, but every x-ray optic distorts the photons in some way. We don't want our mirrors to get in the way of the science."

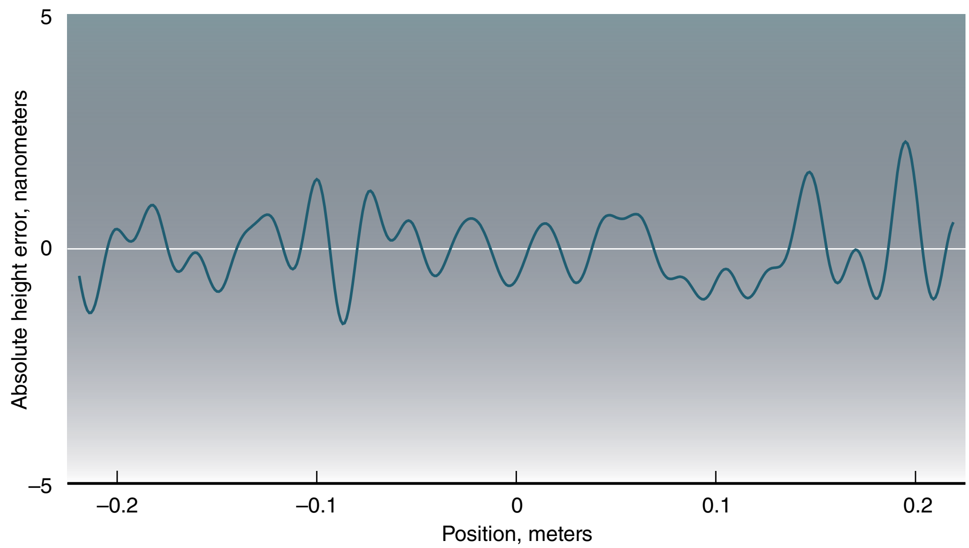
Combining adaptive optics with x-ray mirrors may lead to three significant benefits. First, active control is a potentially inexpensive way to achieve better surface flatness than is possible by polishing the mirrors alone. Second, the ability to change a mirror's flatness allows for real-time correction of aberrations in an x-ray beamline. This capability includes self-correction of errors in the mirror itself (such as those caused by heat buildup) and correction of errors introduced by other optics. Finally, adaptive optics–corrected x-ray mirrors could widen the possible attributes of x-ray beams, leading to new kinds of experiments.

Unlike mirrors used at visible and near-infrared wavelengths, x-ray mirrors must operate at a shallow angle called a grazing incidence. This requirement makes their design and profile quite different from deformable mirrors for astronomy. Traditional x-ray optics are rigid and have a longitudinal, or ribbon, profile up to 1 meter long. If adaptive optics systems can be designed to correct distortions in x-ray beams, next-generation research facilities could offer greater experimental flexibility and achieve close to their theoretical performance.

"As with visible and infrared light, we want to manipulate the x-ray wavefront with mirrors while preserving coherence," says Livermore optical engineer Tom McCarville, who was lead engineer for



Extremely small adjustments to the surface height on the x-ray deformable mirror correct the incoming beam, as depicted in this artist's rendering (not to scale). Unlike visible light, the x rays can only be reflected off the mirror at a very shallow incoming angle, called a grazing incidence. (Rendering by Kwei-Yu Chu.)



In an experiment, high-precision visible light measurements were used to flatten the x-ray deformable mirror to a surface figure error of only 0.7 nanometers average deviation.

the LCLS x-ray mirrors. "The fabrication tolerances are much greater because x-ray wavelengths are so short. Technologies for diffracting and transmitting x rays are relatively limited compared to those available for visible light. Reflective x-ray technology is, however, mature enough to deploy for transporting x rays from source to experiment. Dynamically controlling the mirror's surface figure will preserve the x-ray source's properties during transport and thus enhance the precision of experimental results."

First X-Ray Deformable Mirror

With funding from the Laboratory Directed Research and Development (LDRD) Program, the Livermore team designed and built the first grazing-incidence adaptive optics x-ray mirror with demonstrated performance suitable for use at high-intensity DOE light sources. This x-ray deformable mirror, developed with partner Northrop-Grumman AOA Xinetics, was made from a superpolished single-crystal silicon bar measuring 45 centimeters long, 30 millimeters high, and 40 millimeters wide, the same dimensions of the three hard x-ray mirrors built for LCLS.

A single row of 45 actuators bonded opposite the reflecting surface makes the mirror deformable. These 1-centimeter-wide actuators provide fine-scale control of the mirror's surface figure (overall shape). Actuators respond to voltage changes by expanding or contracting in width along the mirror's long axis to bend the reflecting surface. Seven internal temperature sensors and 45 strain gauges monitor the silicon bar, providing a method to self-correct for long-term drifts in the surface figure.

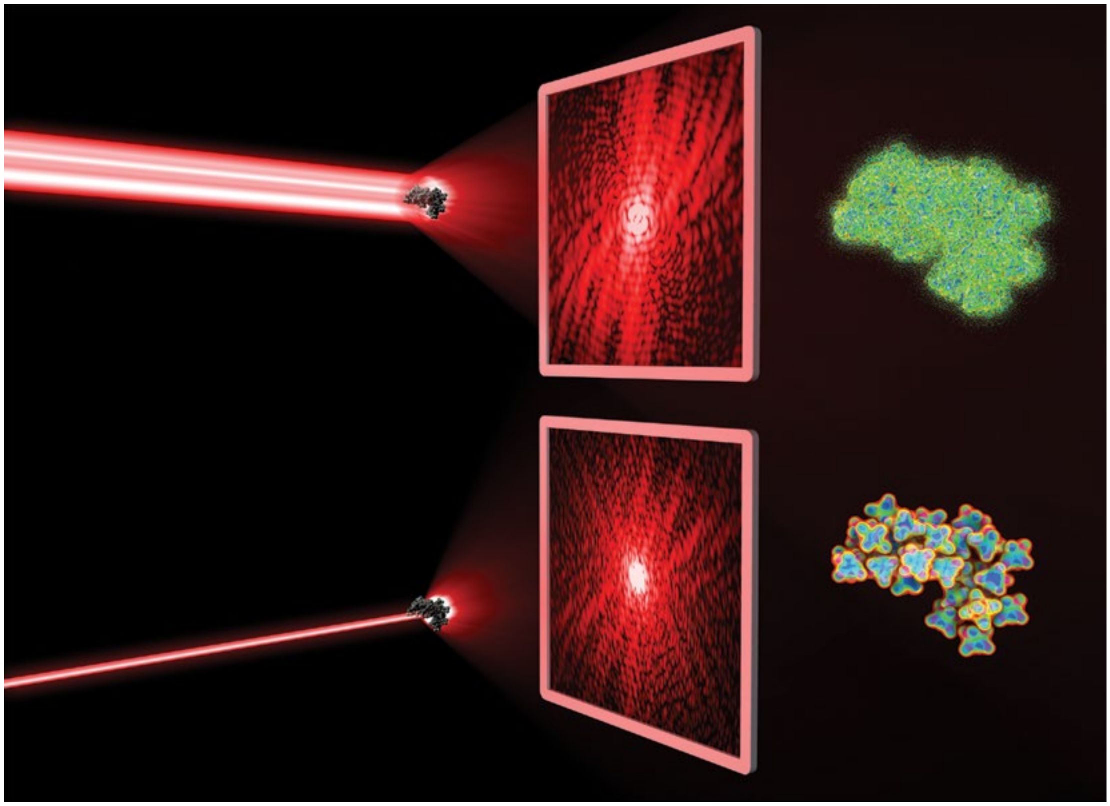
As with all x-ray optics, the quality of the mirror's surface is extremely important because the slightest bump or imperfection will scatter x rays. The substrate was thus fabricated and superpolished to nanometer-scale precision before assembly into a deformable mirror. The initial surface figure error for the deformable mirror was 19 nanometers. Although extremely small, it is substantially above the 1-nanometer-level required for best performance in an x-ray beamline.

To meet that requirement, the team used high-precision visible light measurements of the mirror's surface to "flatten" the mirror. With this approach, interferometer measurements are processed with specialized control algorithms. Specific voltages are then applied to the actuators to adjust the mirror's surface. The resulting figure error was only 0.7 nanometers. "We demonstrated the first subnanometer active flattening of a substrate longer than 15 centimeters," says Poyneer. "It was a very important step in validating our technological approach."

For deformable mirrors to be fully effective, scientists must develop better methods to analyze the x-ray beamline. "We need a sensor that won't distort the beam," says Pivovaroff. Such a sensor would provide a feedback loop that continuously feeds beam characteristics to the mirror actuators so they compensate for inconsistencies in the beam. Poyneer is working on new diagnostic techniques at Lawrence Berkeley National Laboratory's Advanced Light Source (ALS), and the Livermore team is scheduled to begin testing the mirror on a beamline at ALS. The long-term goal of that testing will be to repeat the subnanometer flattening experiment, this time using x rays to measure the surface.

Poyneer is hopeful the adaptive optics research effort will eventually result in a national capability that DOE next-generation x-ray light sources can draw on for new beamlines. She has shared the results with scientists at several DOE high-energy research centers and is working to better understand the needs of beamline engineers and the scientists who use those systems. "There's a lot of interest and excitement in the community because deformable mirrors let us do better science," says Pivovaroff. "The performance of our mirror has surprised many people. Controlling the surface of a half-meter-long optic to less than a nanometer is quite an accomplishment."

By enabling delivery of more coherent and better-focused x rays, the



This artist's concept illustrates the difference in reconstruction quality that adaptive optics could provide if installed at next-generation x-ray beamline facilities. At the top, a partially coherent x-ray beam hits the target object, producing a diffraction pattern on the detector and limiting the accuracy of the recovered image. At the bottom, adaptive optics provide a coherent beam with excellent wavefront quality, which improves resolution of the object. (Rendering by Kwei-Yu Chu.)

mirrors are expected to produce sharper images, which could lead to advances in physics, chemistry, and biology. The technology may enable new types of x-ray diagnostics for experiments at the National Ignition Facility.

Expanded Educational Outreach

The Laboratory's adaptive optics team is also dedicated to training the next generation of scientists and engineers for careers in adaptive optics and is working to disseminate expertise in adaptive optics technology to academia and industry. In a joint project between Lawrence Livermore National Security (the managing contractor for Lawrence Livermore) and UC, two graduate students from the UC Santa Cruz Department of Astronomy and Astrophysics are testing advanced algorithms that could further improve the performance of systems such as GPI. The algorithms are designed to predict wind-blown turbulence and further negate the effects of the atmosphere. Poyneer and astronomer Mark Ammons are mentoring the students, Alex Rudy and Sri Srinath.

Poyneer says, "GPI has demonstrated how continued work on technology developments can lead to significantly improved instrument performance." According to Ammon, "An important frontier in astronomy is pushing adaptive optics operation to visible wavelengths, which requires better control. GPI routinely meets these stringent performance requirements."

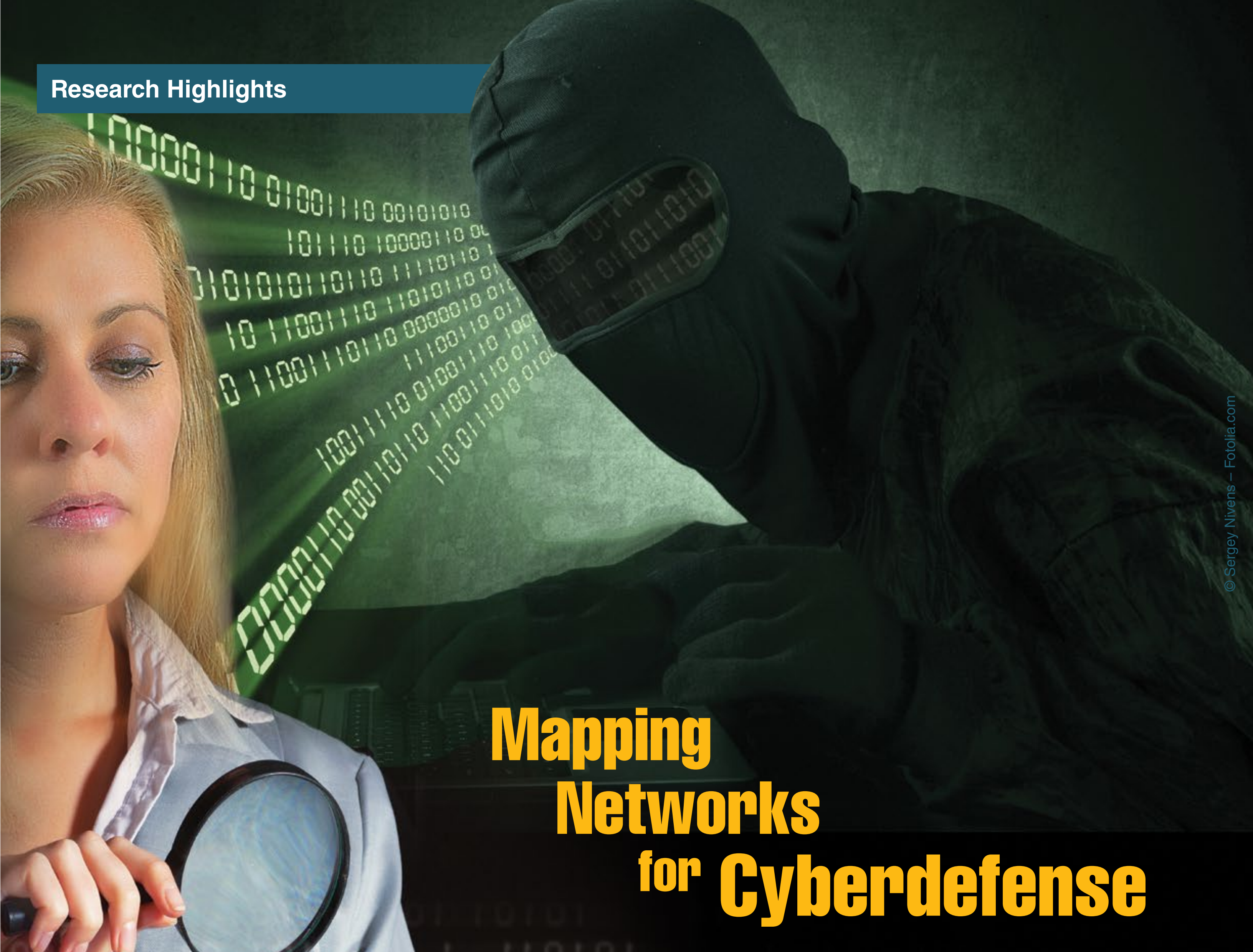
The lessons learned as part of the GPI experience will be critical input for next-generation adaptive optics on large telescopes, such as the W. M. Keck telescopes in Hawaii. Ammons adds, "While adaptive optics were first developed for military purposes, the loop has now closed—the advances made with GPI offer a wide range of potential applications for national security applications."

In addition, the Livermore team is applying its expertise to other fields, as exemplified by progress in the extremely flat x-ray deformable mirror. Thanks to adaptive optics, the universe—from planets to x rays—is coming into greater focus.

—Arnie Heller

Key Words: adaptive optics, Advanced Light Source (ALS), extrasolar planet (exoplanet), Gemini Planet Imager (GPI), Gemini South telescope, Kepler Space Telescope, Laboratory for Adaptive Optics, Linac Coherent Light Source (LCLS), microelectromechanical systems (MEMS), R&D 100 Award.

For further information contact Lisa Poyneer (925) 423-3360 (poyneer1@llnl.gov) or David Palmer (925) 423-1249 (palmer25@llnl.gov).



© Sergey Nivens – Fotolia.com

© Creativa – Fotolia.com

Mapping Networks for Cyberdefense

NEWS reports routinely warn computer users about Internet bugs that threaten the security of important personal information stored online. Large corporations and government agencies are even more vulnerable to bugs and hacking schemes, which may expose critical data that can be used for nefarious purposes. Even with the known potential for damage, few organizations have a complete picture of their vast networks.

Lawrence Livermore has developed a software-based tool called Network Mapping Systems (NeMS) to provide network owners with a comprehensive view of their computer network environments. NeMS builds these visual maps based on observed behavior on the network. It also offers an iterative analysis platform that cybersecurity and information technology personnel can use to explore the maps generated.

"NeMS is a tool for discovering what is actually on a network," says computer scientist Celeste Matarazzo, who worked with colleagues from the

Laboratory's Computation and Engineering directorates to develop the application. A NeMS scan can reveal valuable information such as misconfigurations and other system errors that might make a network vulnerable to attack.

Watching and Probing the Operating Environment

Understanding the components and structure of a computer network and how those resources are used is the first step in many cyberdefense and mission-assurance operations. Mapping software provides a detailed view of a network's topology, including the routers, switches, and end hosts connected to the system and the services running on those devices.

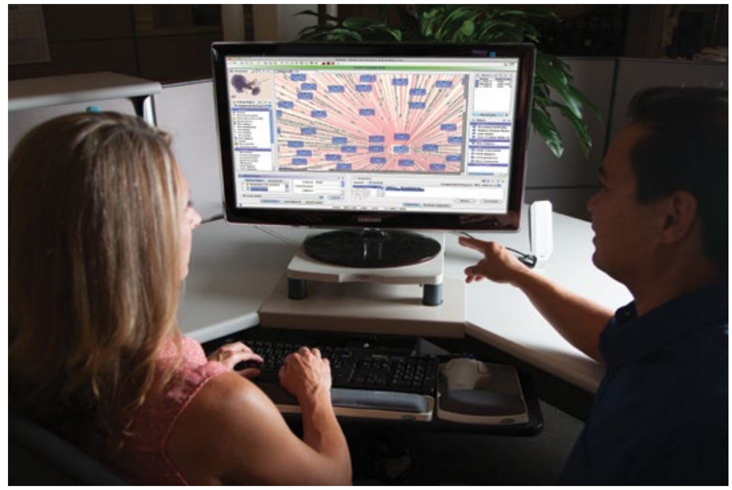
The commercial mapping tools currently available work in either passive mode, which "watches" activity between network targets, or active mode, which scans and probes a network. NeMS combines the two modes—collecting data by watching and probing the network—to more fully characterize the operating environment. NeMS runs on dedicated computer hardware so that scanning does not interfere with network performance and to provide a platform for follow-on analysis. The application can also be implemented as a virtual machine with all the tools needed for mapping, allowing it to operate behind a firewall, on a disconnected system, or on a geographically or logically separated network.

NeMS can characterize a network from multiple vantage points, and merges the results into a single data store for analysis. The software's visualization tools can generate a new map, corroborate or update existing maps, or fuse the data collected with additional information on an organization's network. Having a complete map of the observed operating environment provides what Matarazzo calls "full situational awareness" of the assets, attributes, roles, and logical relationships within a network.

"Computer networks are complex and organic, changing all the time," says Matarazzo. "A NeMS map provides a snapshot of a network's current structure and activity. Repeated mapping offers a picture of how a network is being used and discovers changes that may reveal weak spots or vulnerabilities."

According to Matarazzo, system administrators determine which parts of a network should be characterized. "NeMS does not break through firewalls or scan prohibited areas," she says. "It operates within the parameters set by each client." The mapping routines in NeMS work effectively without extensive preparation or prior knowledge of a network and do not compromise the security posture of the mapped environment. In contrast, current network-mapping tools can be slow and intrusive, and many require special exceptions to network security.

To validate the accuracy of the NeMS mapping techniques, the Livermore team tested the system in both controlled and operational environments. Controlled testing evaluates a network that is offline or otherwise isolated from live (production) operations. In a test with ground-truth information (data similar to that on an active system), NeMS not only identified 100 percent of the network's hosts but also discovered an unknown connection to an external network. The test engineers confirmed that this unexpected connection was in fact valid.



The Livermore-designed Network Mapping Systems (NeMS) collects data by watching and probing a network. It runs on dedicated computer hardware to maintain performance on the network being scanned and to provide a platform for follow-on analysis.

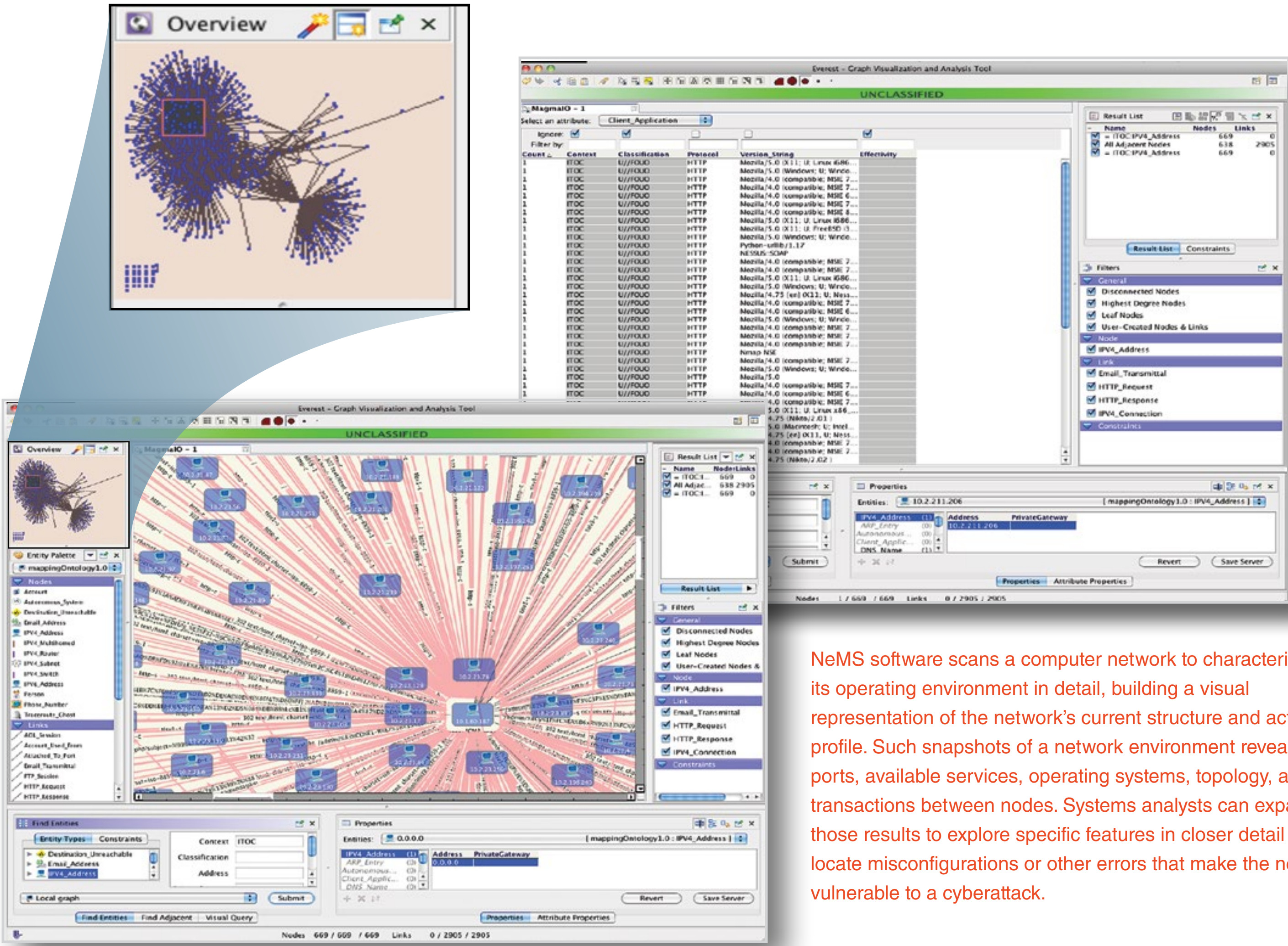
A Plan for Commercialization

The NeMS development team has submitted a patent application on various aspects of the software tool and is working with the Laboratory's Industrial Partnerships Office to find a licensee to commercialize the technology for broader adoption by state and local governments and by private industry. Matarazzo notes that a licensee would have customer service resources not available at a national laboratory and could design a more user-friendly interface for the software.

In product commercialization, developing a new technology is often viewed as the easy part of the process. The more difficult stage is making the technology simple to use and transferring it to a licensee who can effectively market and support the product. This stage has been termed the valley of death because many technologies languish here, often forever.

In 2011, the Department of Homeland Security's Cyber Security Division established the Transition to Practice (TTP) Program to help bridge the valley of death. The program was created in response to the White House's Federal Cybersecurity Research and Development Strategic Plan and the Comprehensive National Cybersecurity Initiative. Its goal is to connect developers from national laboratories with potential licensees and accelerate the transfer of cybersecurity technologies developed with federal funding to a broad audience.

NeMS was a sponsored technology during TTP's first year, and Matarazzo attended the program's May 29, 2014, Technology Demonstration Day for the Energy Sector in Houston, Texas. The



NeMS software scans a computer network to characterize its operating environment in detail, building a visual representation of the network's current structure and activity profile. Such snapshots of a network environment reveal open ports, available services, operating systems, topology, and transactions between nodes. Systems analysts can expand those results to explore specific features in closer detail and locate misconfigurations or other errors that make the network vulnerable to a cyberattack.

event's presentations and demonstrations featured nine technologies from federally funded research and development centers under the Departments of Energy and Defense, each one addressing a unique cybersecurity issue. Attendees—cybersecurity professionals from the energy sector—learned about opportunities for piloting the new technologies and discussed their organizations' areas of interest for future cybersecurity research.

Staying Ahead of Security Threats

Computing and network technology are changing at a rapid pace, often introducing unidentified vulnerabilities. To stay ahead of cybersecurity threats, Matarazzo is leading a Laboratory Directed Research and Development project to take network mapping to the next step. This work involves a larger Livermore team and partners at four universities: Carnegie Mellon, Rutgers, Purdue, and University of California at Davis. The collaboration's new tool, called Continuous Network Cartography, will provide a better understanding of complex or obfuscated computer networks by repeatedly mapping components, services, applications, and their dependencies, showing how they change over time.

Many of the most critical operations in the Departments of Defense, Energy, and Homeland Security depend on complex networks, as do electric smart grids and other parts of the national infrastructure. Decision makers and network operators need to understand an entire network as it evolves, so they can manage assets in a way that prevents intrusions or system failures while allowing defined tasks and missions to be accomplished.

—Katie Walter

Key Words: Continuous Network Cartography, cybersecurity, Department of Homeland Security Transition to Practice (TTP) Program, Network Mapping Systems (NeMS).

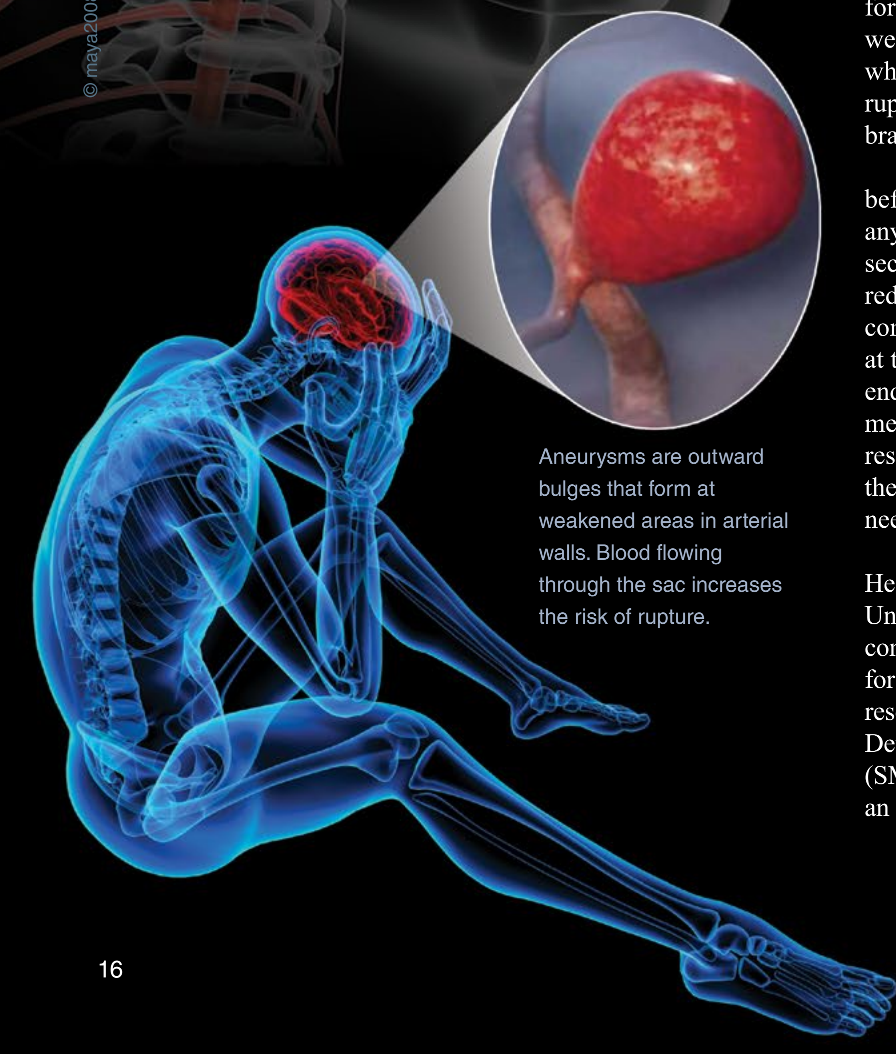
For further information contact Celeste Matarazzo (925) 423-9838 (matarazzo1@llnl.gov).

Foams Help Heal a Deadly Affliction

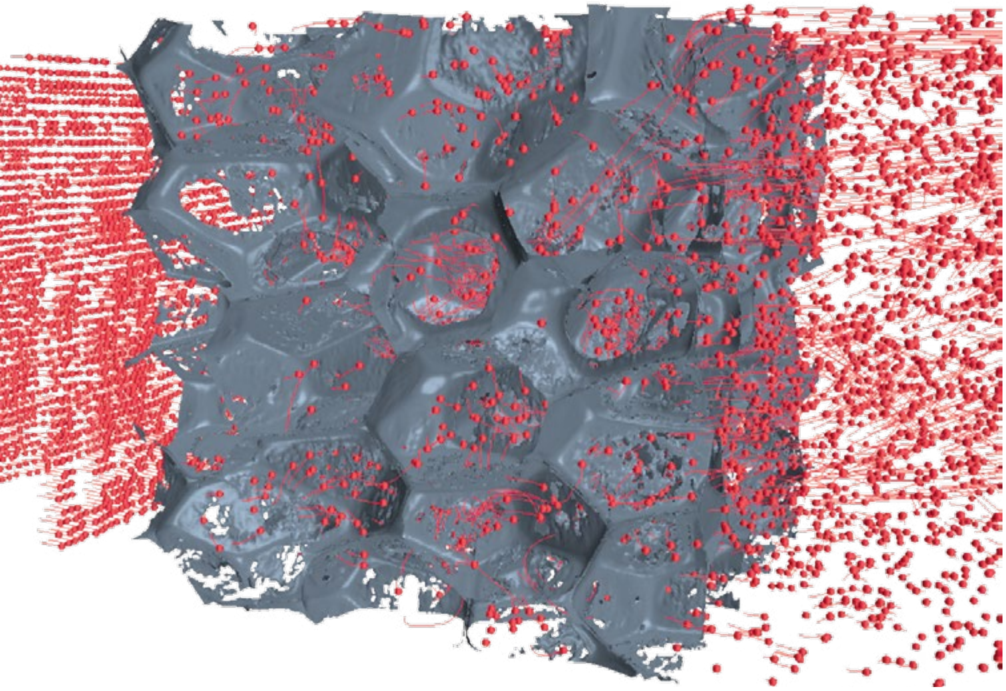
DEEP in the recesses of the human brain can lie a silent, hidden killer—the aneurysm. It lurks among the vast network of arteries, surreptitiously evolving into a life-threatening condition for its unsuspecting victims. These outward bulges form at weakened areas in arterial walls, and the estimated 1 in 15 people who have aneurysms may never display symptoms of a pending rupture. If an aneurysm bursts, blood rushes to other areas in the brain and can cause massive tissue damage, stroke, and even death.

For those lucky enough to be diagnosed with an aneurysm before it ruptures, medical treatment is possible. The goal of any treatment is to isolate the aneurysm sac (the bulged-out section of the vessel) from the rest of the arterial blood flow to reduce pressure on the weakened vessel walls. The two most common treatment methods are either to surgically insert a clamp at the base, or neck, of the aneurysm or to fill in the sac with endovascular metal coils that occlude blood flow. However, both methods have risks. An incorrectly placed clamp can result in residual blood flow. Coils have the potential to unravel or induce the body's inflammatory response, and the insertion process may need to be repeated during a patient's lifetime.

Capitalizing on a five-year grant from the National Institutes of Health (NIH), researchers at Lawrence Livermore and Texas A&M University have combined advanced materials development and computational fluid dynamics (CFD) analysis to improve treatment for intracranial aneurysms. The team's work builds on previous research funded by Livermore's Laboratory Directed Research and Development Program and NIH to develop shape-memory-polymer (SMP) foam that is biologically compatible and can be used to plug an aneurysm before it bursts. (See *S&TR*, May/June 2008, pp. 4–12.)



Aneurysms are outward bulges that form at weakened areas in arterial walls. Blood flowing through the sac increases the risk of rupture.



A computational fluid dynamics simulation illustrates the complex blood flow patterns that arise within and around the closed design for shape-memory-polymer (SMP) foam.

This novel material significantly increases the efficacy of treatment and reduces patient risk compared with the traditional techniques for isolating aneurysms.

SMP foams are a class of polymeric material with extremely low density, enabling them to undergo substantial changes in volume. As a result, these materials can morph from one primary (original) shape into another (temporary) shape and back to their initial forms. Foams designed for treating aneurysms are cut to match the contours of each aneurysm's sac and then compressed to fit inside a catheter for delivery to a specific site inside the brain. Once in place, the SMP foam is activated through temperature change to fill the sac, cutting off blood flow from the main artery and allowing the blood inside the sac to clot.

"Working with the Laboratory's high-performance computers helps us address two main questions about this process," says Jason Ortega, a computational engineer and CFD simulation expert at Livermore. "First, we want to determine what hemodynamic changes occur to blood flow within the aneurysm following the treatment. Second, we want to know whether the foam promotes conditions that are conducive to clotting and aneurysm occlusion."

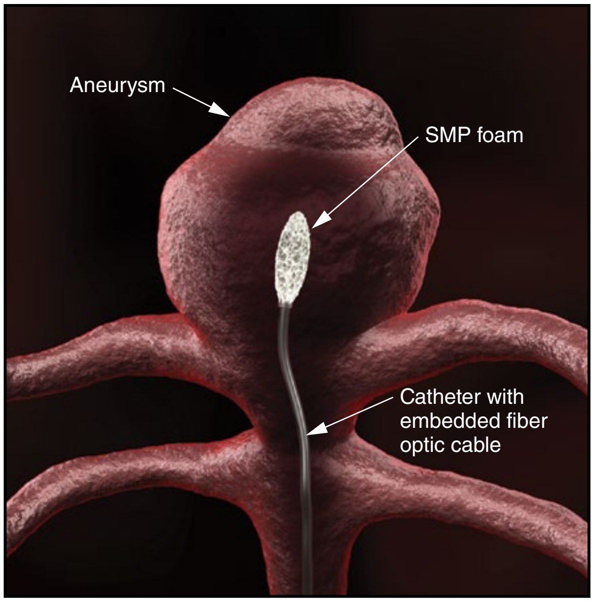
Material scientists then use the simulation results to evaluate how SMP characteristics influence overall treatment. "There is a synergy between computation and chemistry," says chemical engineer Tom Wilson, who led Livermore's SMP development. "The models allow us to assess how blood flow would be affected by an SMP's properties and to alter the material's structure and composition to achieve the desired results." This interrelationship led to insights in design criteria for foam cell size and structure and paved the way for improving the foam's material transition properties, density, and biological compatibility. The CFD work has also provided valuable data for clinicians to use in determining the potential benefits of foam-based aneurysm treatment.

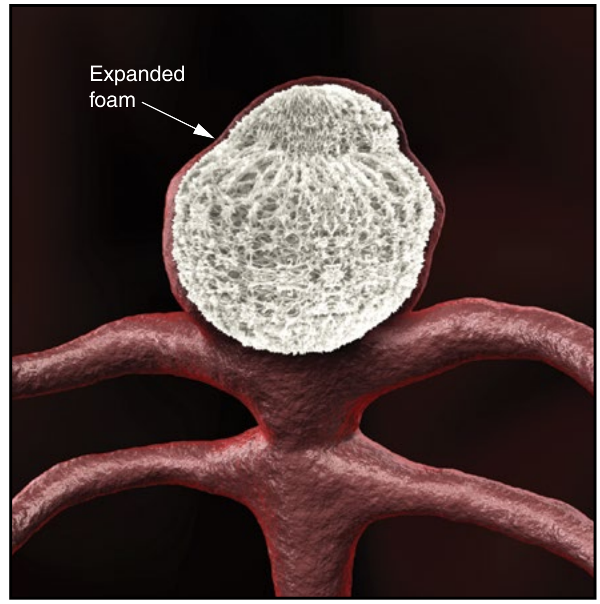
A Dynamic, Virtual Perspective

Understanding blood flow properties, clot (or thrombus) formation, and SMP material behavior inside an aneurysm requires the ability to model multiple length scales. "The models must account for centimeter-sized features of the aneurysm, millimeter-sized pores within the SMP foam, and the micrometer scale of the foam's struts," says Ortega. The team used the STARCCM+ code developed in private industry to achieve the desired resolution.

The models simulate the rheological behavior and velocity of blood flow through an aneurysm, showing how SMP foams change that flow and affect thrombus formation. Foam geometries were obtained using microcomputed tomography to image an SMP sample, which was then virtually refined to produce two foams with different densities: an open SMP with no material between the foam's struts, and a closed SMP in which membranes fill the spatial voids to increase the foam's surface area. The models reveal blood flow patterns within and around different types of foam and illustrate the degree to which each type promotes thrombus formation inside an aneurysm.

Working with patient data provided by a collaborating physician at Kaiser Permanente, Ortega used a high-fidelity CFD simulation to perform virtual angiography on aneurysms prior to and after treatment with the SMP foams. The finely resolved numerical study required approximately 100 million computational cells and produced more than 30 terabytes of data per foam device. The results





Compressed SMP foams are delivered by catheter to an aneurysm sac within the brain. Once it is activated by temperature change, the foam expands to match the sac's contours.

illustrated how the foams reduced velocity fluctuations, increased fluid residence times, and lowered the blood shear rate to promote clotting. "Information from this type of simulation is more relevant to a physician's work than a set of velocity gradients and equations would be," says Ortega. "The models provide a dynamic simulated view of what clinicians observe during an actual angiography procedure and can be tailored to patient-specific details."

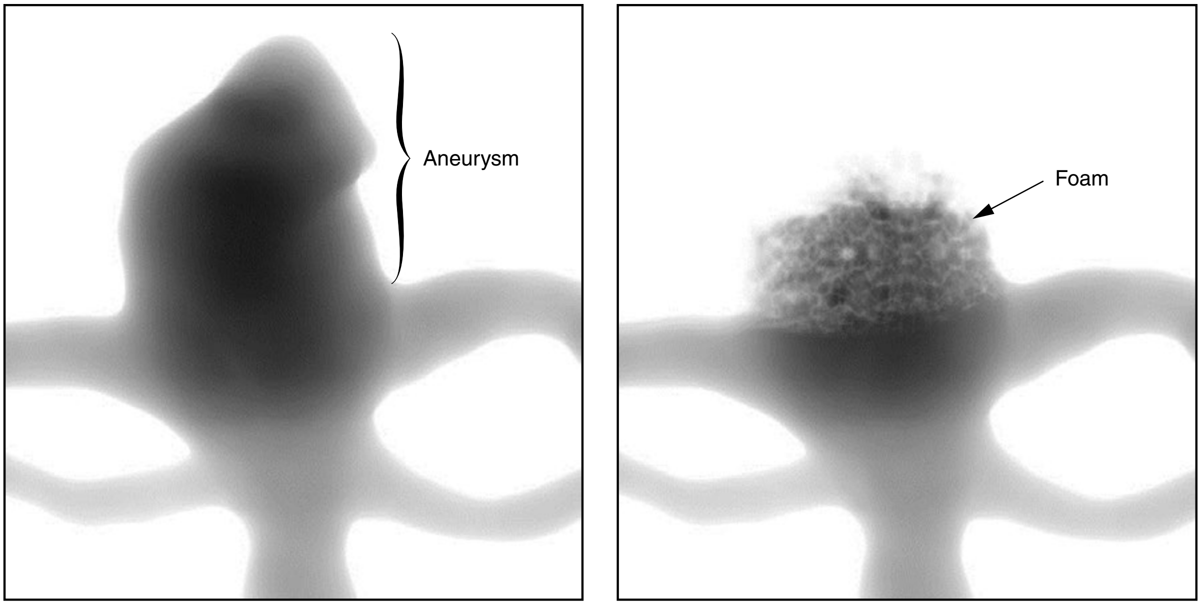
The results revealed that the closed SMP design is highly effective at increasing blood residence time within an aneurysm, which reduces blood flow and better occludes the aneurysm. Additional models demonstrated the effectiveness of different foams at inducing thrombus formation. Results confirmed predictions that the closed SMP design would offer a higher clotting potential in the minutes following treatment, with 26 percent of the aneurysm volume promoting thrombus instead of the 1 percent achieved with the open SMP design. Through this CFD work, the team quantitatively validated the efficacy of a particular foam structure and provided important details on the clotting process required to stabilize an aneurysm.

A More Functional Foam

In tandem with the computational work, Wilson and Livermore materials engineer Ward Small collaborated with colleagues at Texas A&M to refine and experimentally test material characteristics of the SMP foams. "Texas A&M students worked under our direction at Livermore and at College Station to improve the foams," says Wilson. Enhancements included increased hydrophobicity, decreased density, and improved biocompatibility.

SMPs would typically be activated within an aneurysm by an internal or external heat source, such as body temperature or a laser. However, foams must remain relatively resistant to water and other fluids until they can be properly placed in an aneurysm. Lawrence Scholar Pooja Singhal, who worked on the project as part of her graduate work at Texas A&M, adjusted the chemistry of the foam, in particular its monomer structure, to prevent premature expansion and to promote the mechanism by which the material biodegrades in the body.

Singhal integrated low-molecular-weight, symmetric, and polyfunctional hydroxyl monomers into a highly covalent cross-linked polymer structure, which maintains the mechanical properties and low density of SMPs but allows the degradation rate to be controlled. "Originally, SMP foams were designed to be biologically stable, meaning they would remain in the body but not degrade," says Wilson. "Biostable SMPs were developed by creating monomer materials without ether or ester links. When the need arose for biodegradable foams, we selectively added oligomeric caprolactone—an ester-linked chemical group—into the polymer network." Together, the hydrophobicity and caprolactone content control the degradation rate.



During an angiography procedure, a contrast agent is injected into the blood vessel and imaged using x rays to show how blood flows through the vessel. This virtual angiography simulation illustrates a patient-specific aneurysm before (left) and after (right) treatment with SMP foam. The foam reduces the flow (dark areas) and increases the blood residence time to promote clotting.

Additional adjustments to the material's composition and the foaming process reduced the foam's density from 0.020 to 0.008 grams per cubic centimeter, thereby increasing the SMP's volume expansibility within an aneurysm. The temperature at which a compressed foam plug resumes its primary shape is called the glass transition temperature. At certain temperatures below the transition, the foam maintains its compressed shape. At higher temperatures, it reexpands to recover its primary shape. "The goal is to heat the material enough for shape recovery to occur but to keep the actuation temperature low enough to prevent damage to the tissue," says Wilson. By reducing density and controlling the glass transition temperature, the team produced SMP foams with 100-percent shape recovery suitable for aneurysm stabilization.

Developing Customizable Solutions

Wilson notes that the relationship between Lawrence Livermore and Texas A&M has been pivotal to the success of this project. "While we have focused on the materials development and computational work, our partners at Texas A&M have conducted experimental studies and proved the device's functionality," he says. The team is now working to obtain funding for the required regulatory tests and subsequent clinical trials, which would be performed by Texas A&M. Wilson adds, "Because we have the appropriate agreements in place and the partnership is well established, it would be relatively inexpensive for us to collaborate on future projects together."

From a computational standpoint, Ortega sees value in planned efforts to predict the posttreatment outcome of foam-filled aneurysms and to model the complete healing process from initial delivery of the foam to final endothelial cell growth over the aneurysm opening. "More experimental data would be needed to validate the codes," he says, "but the future possibilities are exciting."

By combining high-performance computing and advanced materials development, the team has moved one step closer to offering a more efficient, less risky option for treating aneurysms. "Ideally, the foams could be tailored to each patient's needs to promote a more successful outcome," says Ortega. Biomedical breakthroughs such as this one improve the chances for preventing debility from deadly afflictions, allowing more people to enjoy healthy, productive lives.

—Caryn Meissner

Key Words: aneurysm, blood clot, computational fluid dynamics (CFD), high-performance computing, materials engineering, shape-memory-polymer (SMP) foam, thrombus.

For further information contact Tom Wilson (925) 422-5519 (wilson97@llnl.gov) or Jason Ortega (925) 423-3824 (ortega17@llnl.gov).

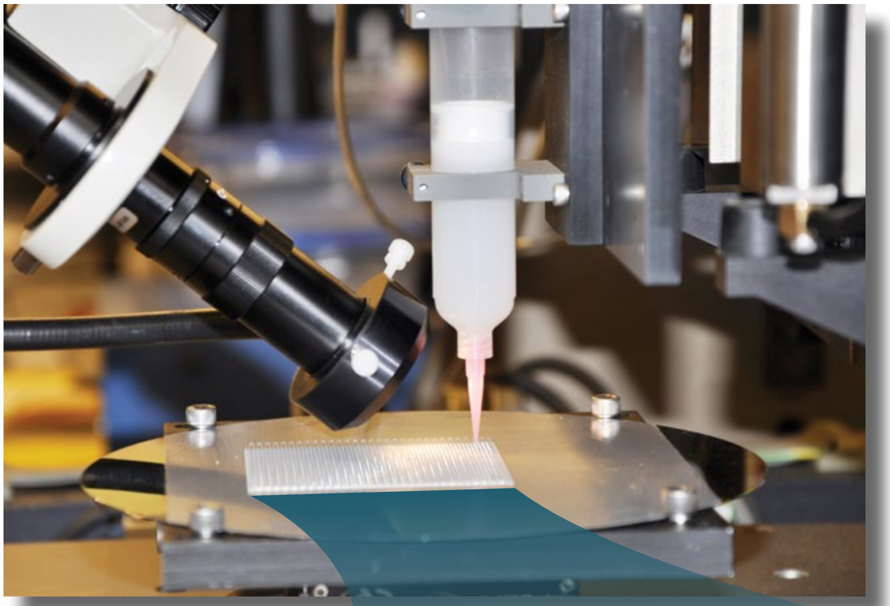
Additive Manufacturing Reshapes Foam Design

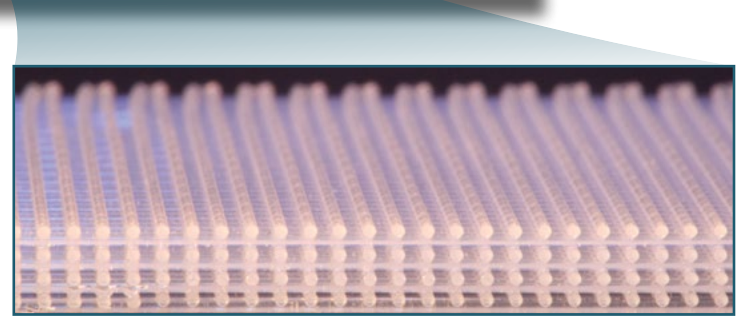
Livermore engineers Eric Duoss (left) and Tom Wilson use an additive manufacturing (AM) process called direct ink writing to develop an engineered “foam” weapon cushion.

OVER time, high radiation fields, temperature swings, and other environmental factors can cause the foam parts inside nuclear weapons to lose their resiliency and shrink. These foams, which absorb shocks and fill gaps between components, must then be replaced during weapons maintenance and refurbishment activities conducted under life-extension programs (LEPs). (See *S&TR*, March 2012, pp. 6–13; July/August 2010, pp. 4–11.) The Laboratory’s production counterpart, the National Nuclear Security Administration’s Kansas City National Security Complex, produces the durable silicone-based cellular foams used in Livermore-led LEPs and ensures that these foams meet the chemical, structural, and mechanical standards established for weapon components.

Foams are by nature disordered materials studded with air pockets of varying sizes. As such, a manufacturer’s lack of control over the material’s architecture at the micro- or nanometer scale can make it difficult to tailor a foam’s properties. The material response of cellular silicone foams can be adjusted during the manufacturing process by modifying the foam formula or the spacing and concentration of air pockets. However, the response range is limited, and the process is imprecise. Some fabrication steps may also prevent the foam from achieving optimal mechanical properties. In particular, the additive used to form air pockets can prevent the foam from curing thoroughly.

To improve the performance and durability of these crucial components, Livermore weapons engineers and materials scientists, together with their Kansas City partners, are using additive manufacturing (AM) to develop an engineered “foam” with a more controlled structure and tailored properties. (See *S&TR*, March 2012, pp. 14–20.) Additive manufacturing builds structures and components layer by layer from the bottom up, guided by a three-dimensional computer model. First developed in the 1970s, the AM technique has been adopted more widely in recent years thanks to advances in materials, sensors, micromechanics, computational modeling, and simulation. A precise yet flexible method, AM allows researchers and technicians





(top) Livermore's three-axis AM printer uses direct ink writing to print a foam material. The AM process provides more control over the shape and properties of the fabricated object (inset) than conventional manufacturing methods.

to customize a foam's microstructure and behavior and engineer foams with novel combinations of properties, such as being stretchy at one end and stiff at the other.

Product of Perseverance

Livermore's efforts to redesign foam cushions for nuclear weapons began in 2011. Tom Wilson, a chemical engineer and weapons expert in the Laboratory's Physical and Life Sciences Directorate, approached AM specialists Chris Spadaccini and Eric Duoss in Engineering about applying a technique called direct ink writing (DIW) to foam cushion fabrication. DIW uses micro- or nanometer-scale nozzles to deposit, or print, a fine stream of material, often referred to as ink, onto a substrate in a predetermined pattern, similar to toothpaste being extruded from a tube. As the ink is deposited, it quickly solidifies, leaving spaces inside the printed part. Heat or ultraviolet light then cures the ink, linking the interfaces chemically and enhancing the material's strength and cohesion.

Intrigued by the concept, Spadaccini and Duoss developed a DIW-printed prototype made with ultraviolet-cured silicone ink. The engineered foam worked well for about six weeks but then became brittle and crumbled. The effort might have ended there but for the collaborators' perseverance. A heat-cured, silicone-based commercial ink they eventually found produced an engineered foam that was similar in composition to cellular silicone foams and met or exceeded all the performance specifications.

As the researchers experimented with the second-generation ink, interest in this AM application grew at both Lawrence Livermore and Kansas City. Bob Maxwell, who leads the Chemical Sciences Division in Physical and Life Sciences, was an early proponent. "One problem with the traditional way of making foam is that it can take a year or longer to create an effective new formulation," he says. "With additive manufacturing, we can change the properties in hours and develop a candidate material in days, not years. Mistakes, redesigns, and experiments no longer represent a sizable expenditure of effort."

DIW foam production could offer significant advantages over conventional methods. Fabricating the minimum 45-kilogram batch of the current cellular silicone foam takes six weeks. With AM, parts can be fabricated on demand, rather than in large lots, within hours or days. Setup time is also minimal. "With additive manufacturing, we can print one density or pattern of structure in the morning and a different one in the afternoon," says Wilson. "That's harder to do with cellular foam."

The equipment is also compact and flexible. The Laboratory's partners in Kansas City estimate that switching to AM would allow them to shrink production facilities from 1,000 square meters to less than 50. More importantly, AM printers can create part shapes, microstructure patterns, and feature sizes that conventional manufacturing techniques cannot achieve. For instance, some Livermore-designed DIW foams have features only 150 micrometers in diameter—finer than those in cellular silicone foams.

More Predictable Behavior

The Livermore team is using experiments and modeling to characterize the foam's properties and confirm that DIW foam is suitable for stockpile stewardship applications. Results to date indicate that engineered foams display superior structural uniformity to conventional foams, both within a part and between parts. At strain rates relevant to weapon cushioning, engineered foams demonstrate desirable and consistent load responses, a measurement of how the material bounces back when twisted, sheared, or squeezed. "These results are encouraging," says Duoss. "We think we can shrink the ranges of acceptable properties for weapons cushions and create more reliable, uniform, and useful foams. Our success will depend on our ability to understand and accurately predict the material's behavior."

To determine how the microstructure of engineered foams affects material response, the team designed and printed samples with a uniform density but different crystal lattice structures. One sample featured a stacked pattern that repeats every two layers. The other had a staggered configuration that repeats every four layers. The team then examined each sample using in situ synchrotron radiation microtomography to track material response to applied stress. As expected, the two designs behaved differently. The stacked structure became unstable and buckled under compressive loading, while the staggered structure displayed little lateral deformation.

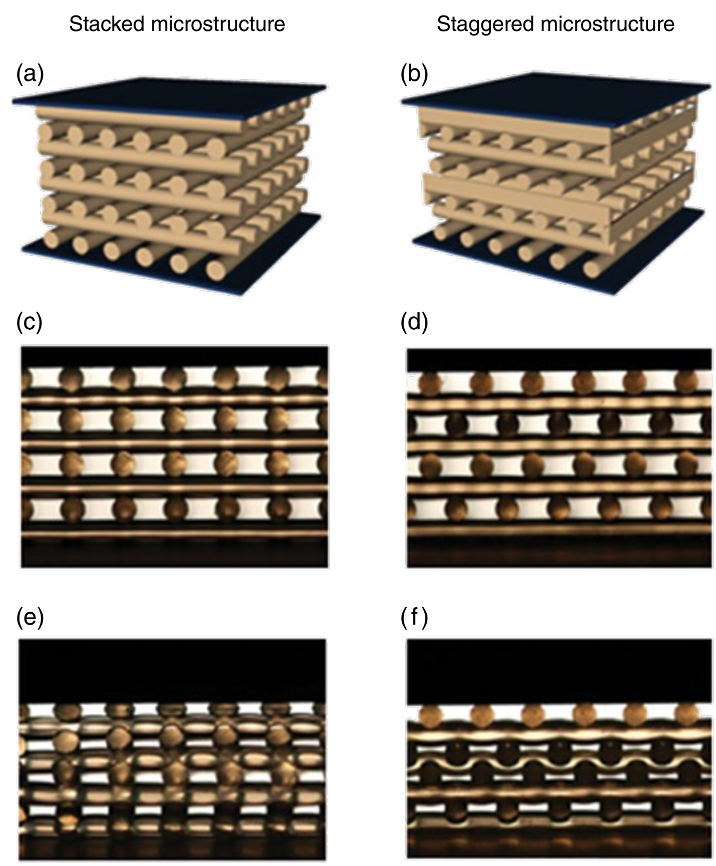
The researchers evaluated both designs by creating finite-element models with NIKE3D, an implicit solver developed at Livermore. The simulations predicted that the stacked structure would experience higher compressive stress than the staggered structure for a given strain—findings that were consistent with observed behavior. In addition, when the stacked structure is compressed, the simulated load is carried in columnar paths that are initially stiff but inherently unstable. The staggered component demonstrated a more distributed load path under compression, giving it a softer response.

That the researchers could accurately predict and study foam behavior through modeling is itself a notable achievement. The greater variability in structure and properties that characterize conventional foams often hindered predictive modeling and forced experts to incorporate a level of uncertainty into stockpile models. The team's modeling efforts will not only benefit foam development in the near term but should also contribute to future stockpile stewardship analysis and certification efforts.

Certification Hurdles Remain

Engineered DIW foams show great promise for replacing cellular silicone foams, but several milestones remain before such parts can be incorporated into a weapon. In the project's early stages, the Livermore team used a three-axis positioning system to print foams with simple shapes just a few centimeters in diameter. In 2014, researchers began working with a six-axis printer to produce three-dimensional foam structures 15 centimeters in diameter.

The team is transferring the process to a five-axis printer at Kansas City. Some printed cushioning and spacing components could be far larger—up to 36 centimeters in diameter and 18 centimeters high—and have more complex shapes. For LEP

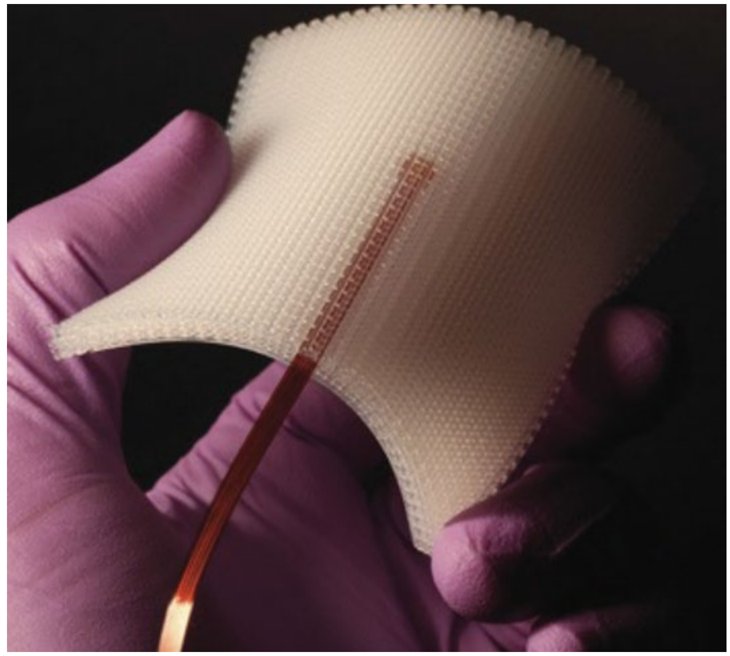


With AM, designers can control the microarchitecture of a material, engineering foams with specific and uniform mechanical responses. A Livermore team evaluated sample weapons cushions with two crystal lattice structures: (a, c) stacked and (b, d) staggered. The two structures had significantly different responses under uniaxial compression of (e, f) 25 percent.

applications, the printer must quickly print parts that precisely match the shape of the current cushions in a designated warhead. A 15-centimeter-diameter sample with a 250-micrometer feature size currently takes several hours to print. Ultimately, complete parts must be produced in 12 to 24 hours to meet anticipated production demands.

In addition, the Livermore–Kansas City team must certify the AM parts through testing and modeling. All warhead components, even foams, are expected to remain functional under the extreme conditions inside a nuclear weapon for 30 to 50 years. Foams must undergo a series of certification tests to gauge their long-term mechanical response and chemical compatibility with other weapon components. Modeling allows the team to accelerate aspects of the certification process without sacrificing accuracy.

As part of the testing, parts are subjected to cyclical or sustained loads while being bombarded with radiation, heat, or both to simulate the effects of material aging. At certain intervals, researchers measure a component's properties and compare the results to those of unaged samples. Critical parameters for weapons cushions include load retention—how well a foam retains its shape under loading—and compression set—how much the foam springs back after a load is removed. Certification also entails searching for chemical incompatibilities in the different materials used in a warhead and confirming through modeling and analysis that the foams will not impede weapon performance. Studies are ongoing, and Livermore engineers are confident the new cushions will eventually meet all mission specifications.



Stress sensors embedded in foams with direct ink writing track contact stress with more consistency and reproducibility than standard stress sensors in weapons cushions. The highly accurate data recordings help weapons experts diagnose age-related issues with the foam and the objects it is cushioning.

A Pattern for Success

Laboratory researchers are exploring ideas to enhance engineered foams. For example, they are developing an ink that will meet performance requirements over a broader temperature range than is possible with the commercial ink currently used. The custom ink will allow them to modify a foam's tensile behavior by adjusting the ink formula. They are also evaluating the usefulness of foam structures designed with directionally dependent or regionally specific properties. "Having different tensile or shear properties within the same component is a remarkable and unprecedented level of material property control at those scales," says Maxwell. He notes that industrial companies are also interested in licensing and customizing the Livermore materials for commercial applications.

Another effort involves embedded sensors, which can be placed in a foam during printing and chemically bonded to it during curing. Installing engineered foam with embedded sensors during an LEP would allow weapons experts to continually monitor the foam's material properties and the weapon's overall condition, or "health," as it ages. Preliminary stress testing indicates that results delivered by embedded sensors in AM foams are 10 times more consistent than those produced by cellular foam sensors. Livermore researchers attribute this improvement to the sensor's secure positioning within the foam and the foam's structural uniformity, features that help them calibrate the sensor and accurately determine the load response. The team is also investigating whether these measurement capabilities could be integrated into the foam structure itself, thereby eliminating the sensor's extra weight and bulk.

Flexible, stretchable AM foams with designed mechanical properties are the newest chapter in the Laboratory's history of developing novel materials for diverse applications. Aided by a multidisciplinary approach that integrates precision engineering and manufacturing expertise, materials science research, and high-performance computing, Lawrence Livermore has emerged as an AM leader among Department of Energy laboratories. Advances in AM technology may eventually be applied to such areas as aerospace, national security, consumer electronics, energy, and even sporting goods. "This research is bigger than just polymer materials," says Duoss. "We've helped shape the Laboratory's overall direction with additive manufacturing."

—*Rose Hansen*

Key Words: additive manufacturing (AM), direct ink writing (DIW), life-extension program (LEP), NIKE3D, nuclear weapons cushion, silicone-based cellular foam, stockpile stewardship.

For further information contact Thomas Wilson (925) 422-5519 (wilson97@llnl.gov) or Eric Duoss (925) 423-4993 (duoss1@llnl.gov).

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Nanoengineered Field Induced Charge Separation Membranes and Methods of Manufacture Thereof

Kevin C. O'Brien, Jeffery J. Haslam, William L. Bourcier
U.S. Patent 8,696,882 B2
April 15, 2014
According to one embodiment, this device includes a porous membrane having a surface charge and pore configuration characterized by a double layer overlap effect in pores of the membrane. According to another embodiment, the device includes a porous membrane with a surface charge in its pores sufficient enough to impart anion or cation selectivity in the pores. Additional devices, systems, and methods are presented.

High Effective Atomic Number Polymer Scintillators for Gamma Ray Spectroscopy

Nerine Jane Cherepy, Robert Dean Sanner, Stephen Anthony Payne, Benjamin Lee Rupert, Benjamin Walter Sturm
U.S. Patent 8,698,086 B2
April 15, 2014
One scintillator material is designed with a bismuth-loaded aromatic polymer that has an energy resolution of less than about 10 percent at 662 kiloelectronvolts. Another scintillator material includes a bismuth-loaded aromatic polymer that incorporates a fluor and has an energy resolution of less than about 10 percent at 662 kiloelectronvolts. Additional systems and methods are presented.

Method and System for Dual Resolution Translation Stage

John Michael Halpin
U.S. Patent 8,702,080 B2
April 22, 2014
This dual resolution translation stage includes a stage assembly designed to receive an optical element and a low-resolution adjustment device mechanically coupled to the stage assembly. The dual resolution stage also includes an adjustable pivot block mechanically coupled to the stage assembly. The pivot block contains a pivot shaft and a lever arm that swings about the shaft. The dual resolution stage additionally features a high-resolution adjustment device mechanically coupled to the lever arm and the stage assembly.

Nanoporous Carbon Tunable Resistor/Transistor and Methods of Production Thereof

Juergen Biener, Theodore F. Baumann, Subho Dasgupta, Horst Hahn
U.S. Patent 8,703,523 B1
April 22, 2014
In one embodiment, a tunable resistor–transistor includes a porous material that is electrically coupled between a source electrode and a drain electrode. The porous material acts as an active channel saturated by an electrolyte solution that is adapted for altering an electrical resistance of the active channel based on an applied electrochemical potential. The active channel comprises nanoporous carbon arranged in a three-dimensional structure. In another embodiment, a method for forming the tunable resistor–transistor includes forming a source electrode, forming a drain electrode, and forming a monolithic nanoporous carbon material that acts as an active channel and selectively couples the source electrode to the drain electrode electrically. In any embodiment, the electrolyte solution saturating the nanoporous carbon active channel is adapted for altering an electrical resistance of the nanoporous carbon active channel based on an applied electrochemical potential.

Active Noise Canceling System for Mechanically Cooled Germanium Radiation Detectors

Karl Einar Nelson, Morgan T. Burks
U.S. Patent 8,704,186 B2
April 22, 2014
This microphonics noise cancellation system improves the energy resolution for mechanically cooled high-purity germanium detector systems. A classical adaptive noise canceling digital processing system using an adaptive predictor is used in a multichannel analyzer to attenuate the microphonics noise source, making the system more deployable.

Fabrication of High Gradient Insulators by Stack Compression

John Richardson Harris, Dave Sanders, Steven Anthony Hawkins, Marcelo Noroña
U.S. Patent 8,709,572 B2
April 29, 2014
Individual layers of a high gradient insulator (HGI) are precut to their final dimensions and stacked to form an assembly that is subsequently pressed into an HGI unit with the desired dimension. Alignment of the individual stacked layers is maintained with a tube that is removed after the stack is hot-pressed. HGIs serve as high-voltage vacuum insulators in energy storage and transmission structures or in such devices as particle accelerators and pulsed-power systems.

High Gradient Lens for Charged Particle Beam

Yu-Jiuan Chen
U.S. Patent 8,710,454 B2
April 29, 2014
These methods enable shaping of a charged-particle beam. A dynamically adjustable electric lens has alternating layers of insulators and conductors with a hollow center. When stacked together, the alternating layers form a high gradient insulator (HGI) tube that allows a charged particle beam to propagate through the tube's hollow center. Transmission lines are connected to multiple sections of the HGI tube, and one or more voltage sources supply an adjustable voltage value to each transmission. Changing the voltage supplied to each section of the HGI tube will establish the desired electric field across the tube. Functionalities such as focusing, defocusing, acceleration, deceleration, and intensity modulation can be effectuated on a time-varying basis with this method.

RF/Optical Shared Aperture for High Availability Wideband Communication RF/FSO Links

Anthony J. Ruggiero, Hsueh-Yuan Pao, Paul Sargis
U.S. Patent 8,712,246 B2
April 29, 2014
This shared aperture can transmit and receive optical and radio-frequency (RF) signals simultaneously. The technology enables compact wide-bandwidth communications systems with 100 percent availability in clear air turbulence, rain, and fog. The functions of an optical telescope and an RF reflector antenna are combined into a single compact package by installing an RF feed at either focal point of a modified Gregorian telescope.

Abstract

Giant Steps for Adaptive Optics

The newly fielded Gemini Planet Imager (GPI) is deployed on one of the world's largest telescopes, the 8.1-meter-diameter Gemini South telescope in Chile. The heart of GPI is its highly advanced, high-contrast adaptive optics system that measures the wavefront of the light seen through the Gemini South telescope at nearly 2,000 locations and at 1,000 times per second. Even in its shakedown phase, GPI is producing the fastest and clearest images of extrasolar planets (exoplanets) ever made. GPI is perhaps the most impressive scientific example of Lawrence Livermore's decades-long preeminence in the field of adaptive optics. This technology removes distortions that are induced by the passage of light through a turbulent medium, such as Earth's atmosphere, or by mechanical vibration. The Laboratory is also applying its expertise in adaptive optics to correct x-ray beams for a new generation of high-energy research facilities, and outreach efforts are strengthening adaptive optics education in U.S. colleges and universities.

Contacts: Lisa Poyneer (925) 423-3360 (poyneer1@llnl.gov) or David Palmer (925) 423-1249 (palmer25@llnl.gov).

U.S. Government Printing Office: 2014/770-075-10005

Coming Next Issue

Livermore Wins Four R&D 100 Awards

Courtesy of *R&D Magazine*

In *R&D Magazine*'s annual competition for the top 100 industrial inventions, Laboratory researchers won awards for the following technologies:

- microTLC™ (Thin-Layer Chromatography)
- Superconducting Tunnel Junction X-Ray Spectrometer
- Extreme-Power Ultralow-Loss Dispersive Element (EXUDE)
- CISR, a Convergent Polishing Prototype

Also in October/November

• To promote international security, the Laboratory is engaged in several efforts to expand and share its nuclear forensics expertise with collaborators worldwide.

Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

PRSRT STD
U.S. POSTAGE
PAID
San Bernardino, CA
PERMIT NO. 3330

Printed on recycled paper.